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ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT

7 RUE ANCELLE 92200 NEUILLY SUR SEINE FRANCE

AGARD CONFERENCE PROCEEDINGS 521

Advanced Aircraft Interfaces: The Machine Side of the Man-Machine Interface

(Les Interfaces sur les Avions de Pointe: L'Aspect Machine de l'Interface Homme-Machine)

Papers presented at the Avionics Panel Symposium held in Madrid, Spain, 18th–22nd May 1992.

NORTH ATLANTIC TREATY ORGANIZATION

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North Atlantic Treaty Organization

Organisation du Traité de l'Atlantique Nord

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— Recommending effective ways for the member nations to use their research and development capabilities for the common benefit of the NATO community;

— Providing scientific and technical advice and assistance to the Military Committee in the field of aerospace research and development (with particular regard to its military application);

— Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;

— Improving the co-operation among member nations in aerospace research and development;

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Theme

The complexity of the modern battle scenario is demanding better situational awareness for the pilot/crew. The advent of laser weapons capable of blinding a pilot or crew member requires that such radiation should not reach the pilot. This dictates that windowless or severely restricted visibility cockpit concepts be used. Emerging technologies, properly applied, offer potential solutions to answer these conflicting issues.

The present interface between the pilot/crew and the aircraft is evolving to more sophisticated displays represented on a variety of media including CRTs, flat panels, and helmet mounted displays augmented by multi-function switches and voice. The application of these technologies presents both opportunities and special requirements. These requirements include the development and integration of a variety of concepts to enhance the situational awareness while reducing the laser threat.

The exploration of these concepts, their integration in various combinations, and their potential to enhance mission capability was the central theme of this Symposium.

Thème

La complexité croissante des scénarios de combat modernes exige une meilleure perception de la situation pour le pilote ou l'équipage. L'apparition d'armes laser capables d'aveugler le pilote ou un autre membre de l'équipage exige que de tels rayonnements n'atteignent pas le pilote. Ceci impose le recours à des concepts d'habitacles sans vitre ou à visibilité très réduite. Les technologies récentes, si elles sont appliquées correctement peuvent fournir des solutions pour répondre à ces questions contradictoires.

Les équipements d'interface entre l'équipage et l'avion évoluent vers des systèmes complets plus perfectionnés avec affichage de symboles, présenté sur divers équipements tels que les écrans cathodiques, les écrans plats et les visualisations montés sur le casque augmentés de sélecteurs multifonctions et de commandes vocales. Si la mise en œuvre de ces technologies présente des opportunités, elle pose aussi des besoins spécifiques. Ces besoins comprennent le développement et l'intégration de différents concepts pour rehausser la perception de la situation tout en réduisant la menace laser.

L'examen de ces concepts, leur intégration selon différentes configurations, et leur potentiel pour l'amélioration de la capacité opérationnelle, constituaient le thème de ce symposium.

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TECHNICAL EVALUATION REPORT

by

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INTRODUCTION

A Symposium of the AGARD Avionics Panel was held in Madrid, Spain, on May 18 to May 21 1992. The subject of the symposium was "Advanced Aircraft Interfaces: The Machine Side of the Man Machine Interface". The Programme Chairman for the meeting was Mr. William E. Howell of NASA.

THEME OF THE SYMPOSIUM

The complexity of the modern battle scenario is demanding more of the pilot/crew in the aircraft and their need for better situational awareness is progressively increasing. Furthermore, the advent of laser weapons capable of blinding a pilot or crew member is demanding that concepts be used which preclude such radiation reaching the pilot. This requirement dictates that windowless or severely restricted visibility cockpit concepts be used; however the need still exists for complete visibility in all directions and wavelengths, to avoid or engage hostile forces. Emerging technologies, properly applied, offer potential solutions to these issues including retrofit of existing weapons systems to meet the changing requirements.

The present interface between the pilot/crew and the aircraft is evolving to more sophisticated full colour, abstract displays presented on a variety of media including CRT's, flat panels and helmet-mounted displays. The pilot's inputs will still include standard buttons and switches but will be augmented by multi-function switches and possibly voice. The application of this technology presents both opportunities and special requirements. These requirements include the development and integration of a variety of concepts such as CRT Displays, Flat Panel Colour Displays, Helmet Mounted Displays (including helmet optical geometry), Head Up Displays, Night Vision Goggles, Integrated Displays (Visual, IR, Computer-generated symbology), Voice I/O, Multi-Function Display and Input Devices, and Target Acquisition and Aiming Devices.

The exploration of these concepts, their integration in various combinations, and their potential to enhance mission capability were the central theme of the Symposium.

GENERAL DESCRIPTION

The programme consisted of thirty-two papers, divided into seven sessions. Preceding these was a keynote address which provided an excellent introduction to the later, more detailed, papers. Discussion was invited after each paper, but no period was allocated for general or round-table discussions.

TECHNICAL EVALUATION

Session I - Defining Concepts and Design Issues

In this first session it would have been useful had a framework been set for the subsequent sessions. In fact two of the papers provided this in part. C.G.Burge (Paper 3) gave a top-down analysis of the problems in military aircraft man-machine interfaces and listed nine categories which required research, and S.P.Williams (Paper 2) gave a series of examples of cockpit equipments which are being investigated for use in future civil transport aircraft. However, neither author made clear the relationship between the interface design requirements and the characteristics of the avionics or weapons systems with which they were to be integrated.

Professor Bosman (Paper 1) described the characteristics of the human eye and gave some particularly pertinent observations on the scan patterns when reading text or numerals as compared with those when looking at complex scenes; these are of obvious importance when considering display layouts for use at times of high workload. It would have been interesting if the information given on monochrome displays had been extended to colour since almost all displays in modern aircraft are now multi-coloured.

Paper 4 by J.Struck was a description of alternative computer system arrangements for generation of information in a graphical form, an important part of the design of display interfaces. It did not provide any information about the benefits or trade-offs of the alternative designs.

Paper 5, which was presented in the absence of the authors by L.Dopping-Hepenstal, reported on a questionnaire survey of selected British Aerospace pilots concerning the automation of airborne systems. Ten distinct categories of pilot-machine interface were defined, ranging from the pilot performing the entire activity to the system autonomously performing the action. Opinions generally favoured increased use of automation, with pilots wanting to be informed of the effects of faults upon the capability of the aircraft rather than the technical diagnosis of specific types of fault. Direct

intervention into the operation of the flight control system was declared unacceptable.

Session II - Maintenance for Advanced Cockpit Systems

Session II consisted of only two papers. The subject of the session is an important one since it is clearly necessary to ensure that cockpit equipments have adequate availability, reliability and integrity compatible with their role as the link between the aircrew and all the aircraft systems. However it is not apparent that there need be any difference between the maintenance of cockpit systems, which are very largely computer-based, and that of other computer-based onboard equipment. This was confirmed by the two presented papers.

Paper 6, presented by J.A.Collins, was particularly interesting in describing the evolution of a new method of improving maintenance methodology by implanting devices into avionics equipment that would measure and record physical parameters that were judged to affect the failure rates of the equipment into which they had been implanted, for example temperature and shock. Using the outputs from these sensors, together with a model of the predicted failure pattern, it is hoped that many BIT-detected failures which cause system cut-out can be confirmed as soft failures and hence allow system restart.

Paper 7, presented by W.Wurster, described a conventional computer-aided maintenance system which was claimed to be particularly useful during the development phase.

Session III - Panoramic and Virtual Cockpits

Advances in both computer and display technology are bringing closer to reality the concept of the "Virtual World" in which a human operator using all of his input and output mechanisms can believe himself to be in a real world which responds correctly to any action which he cares to make even though this world has actually been created artificially. As applied to aircraft, Virtual Cockpits are usually taken to mean cockpits in which the pilot's visual scene, including both the outside world and the instrument panel, are created and displayed artificially, while aural and touch sensors are also fed from computers through suitable transducers. Paper 8, presented by W.L.Martin, described a USAF development programme in this area. The absence of any detailed engineering data, such as the resolution obtainable from the displays, or any results of trials, significantly reduced the value of the paper and made it impossible to assess whether the concept is likely to become an effective and useful interface in the forseeable future.

Paper 9, presented by D.G.Hopper, described another USAF programme, this one concerned with simulator trials of a very large centrally-mounted head-down display. The display was used to provide better situational awareness for a pilot in air-to-air combat than that used in the standard F-15. Significantly improved kill ratios were claimed.

Paper 10, by P.Larroque and R.Joannes, also described a development programme leading up to simulator trials, in this case of low-level penetration flights in poor weather or at night. The technique used was to create a synthetic display of the outide world, based on a data base created from reconnaissance and map information. The results from the first series of trials were encouraging, with positive pilot acceptance, and this will lead to further phases which will include studies of integrity and of combining the images from onboard sensors with the synthetically-created data.

Session IV - Helmet Mounted Displays

Session IV was the biggest of the Symposium with 7 papers, although one (Paper 14) was not presented. This reflects the continuing interest in helmet-mounted displays as an R&D topic in spite of the persistant difficulty in finding engineering solutions to the intrinsic problems of mounting wide-angle, high-resolution displays on a helmet in such a way that the overall helmet design is compatible with all the safety and usability criteria for military aircraft use.

The use of diffractive optics is one way of finding an acceptable solution to the problem of providing wide field of view displays close to the pilot's eyes. Paper 11, presented by G. de Vos, gave an account of the design trade-offs and explained that the need to reduce weight required that relay optical elements should be minimised and hence that the holographic elements should not be far off-axis. A novel design of visor hologram was described which reduces chromatic aberration.

Paper 12, given by S. Williams, provided guidelines on the possible application of stereoscopic helmet-mounted displays to a number of different types of aircraft operation. The most clear-cut advantages were found in the precision hover of rotorcraft; for other operations such as a tracking task and a curved approach to landing, the gain in performance was found to be significantly less.

J.P.Cursollè gave paper 13 on the subject of applications of helmet-mounted displays to the operation of combat aircraft at night and in all weather. The pilot's need for "contact" flying was explained as well as the essential characteristics of a helmet-mounted dislay appropriate for this type of operation.

Paper 15, which was presented by A.Karavis and T.Southam, described the MOD(UK) programme which is attempting to develop a fully-engineered helmet which will meet a design specification appropriate to a high performance combat aircraft. The helmet will carry a binocular wide-angle display and a pointing pickoff, as well as the normal fittings such as facemask. The detailed specification was presented, which has been derived from earlier MOD experience of flying non-integrated helmet-mounted displays.

Paper 16, by J.P.Foley, descibed optical techniques which can be used to provide protection to the pilot's eyes against damage resulting from flashes and lasers. A good analysis was given of the available technologies, both passive and active.

W.E.Howell presented Paper 17 which gave an assessment of the use of synthetic vision for the approach and landing of civil transport aircraft. He described trials carried out by NASA in a Boeing 737 aircraft in which the landing accuracy was found to be approximately equivalent to that obtained with normal vision. Although the experiments were principally directed to the use of synthetic vision on future spacecraft, the results have significance for military aircraft as well.

Session V - Voice Technology

Voice forms a natural means of man-to-man communication which has always been extensively used in military aircraft, and experiments have been conducted for several years to develop the technology for use in both man-machine and machine-man roles. Session V comprised five papers which gave a reasonable overview of the curret state-of-the-art in this area.

Paper 18 by Professor N.Ince gave a good introductory review of speech coding, compression and recognition, of which only synthesis and recognition can really be considered man-machine interface techniques. For synthesis, a high probability of successful operation is now available from relatively cheap off-the-shelf equipment. Voice recognition is much more difficult, and hence most systems have to accept severe limitations such as reduced vocabulary and speaker dependance. Even with these limitations there is less than 100% probability of correct recognition which implies that for most applications supplementary verification will be necessary.

Paper 19 by F.Hollevoet concentrated on voice recognition and gave a description of the recognition process in a typical system. It provided a useful reinforcement of many of the points made in Paper 18.

Paper 20, presented by B.Barbier, gave a description of some preliminary experiments to study possibilities for future cockpit layouts. They explored the possibility of using multiple inputs from the pilot such as eye movement, voice input, and hand and head position transducers. Unfortunately, the results of the experiments were not given.

Paper 21 was given by M.M.Taylor, and provided a description of the psychological background to communication including the use of voice as the communication medium in a man-machine control loop. The author developed a rather philosophical discussion of the principles of man-machine interface and the sharing of control between pilot and aircraft system.

C.Gulli presented paper 22 which gave an account of an experimental programme on voice recognition exploring the effects on recognition performance of influences such as cockpit noise, g-loading and oxygen mask. Experiments carried out in a centrifuge showed that the recognition performance should not be affected by g-loads if proper compensation is provided; this is encouraging as acceleration effects are often quoted as a major problem. A good presentation of the experimental results was given. The author expressed optimism about future possibilities while emphasising the necessity for more research.

Session VI - System Design Concepts and Tools

Session VI was principally concerned with the methodology of the design and development of the man-machine interface, but inevitably several of the papers also discussed some of the broader issues concerning the relationship between the interface and the total aircraft/aircrew system. Perhaps because of these wider systems implications, the discussions following each paper were noticeably more lively than they had been in earlier sessions.

Paper 23 by F.Armogida discussed the reduction of pilot workload in critical phases of a combat mission by the mechanism of transferring work to earlier phases of the flight. He advocated more use of airborne mission planning and its proper correlation with pre-flight mission planning. This was an important paper in recognising that man-machine interface problems are profoundly affectd by the design of the complete system.

Paper 24 by E.Lovesey was largely devoted to a historical perspective on cockpit design problems. Its main interest was that it was one of the very few papers in the symposium which even mentioned the aircrew problems in large multicrew aircraft and the need to consider the internal distribution of information and of tasking.

Paper 25 by C.R.Ovenden described some investigations of cockpit warning systems for use in civil transport aircraft, but having implications for military aircraft as well. The intention is to develop diagnostic systems which would monitor the health of aircraft equipments and systems and be able to advise the crew on corrective action which should be taken in advance of total failures. This very desirable objective can only be achieved by the development of models of system behaviour which take into account failure trends and hence appears likely to be most applicable to mechanical systems such as engines. No information was provided on how far the work has progressed.

Paper 26 was presented by L.Dopping-Heponstal and described the design process adopted for the cockpit and systems of the Eurofighter. The process featured a very structured approach in which the information flow and the crew workload during a small number of well-defined missions were analysed in detail. The methodology provided for a lot of analysis and work-station testing before commencing mock-up trials.

C.Weber (Paper 27) described a cockpit design and development tool which had been used in the development of the "Tiger" helicopter. By contrast with the methodology described in paper 26, it appeared that this was based on the use of a mock-up right from the start of the design process. A good description was given of the experimental results obtained, which included both performance analysis and aircrew opinion ratings.

Paper 28 by M.P.Kibbe was a description of the use of automatic target recognition systems in aircraft and their acceptability by aircrew. It was stated that, for various reasons, automatic systems require aircrew back-up, and that to make this effective the crew need to have trust in the system and to be informed of the source of the recognition data. The experiments for both identification and recognition of ships were described; the results were not clear-cut and depend on the reliability of the performance of the automatic recognisers.

Session VII - Device Technologies

It was rather surprising that only four papers were presented in the Device Technologies Session, of which only the first two could reasonably be described as papers about devices. This is perhaps a reflection of a growing awareness that most of the main challenges in the man-machine interface are concerned with the total system rather than the interface devices themselves. Nevertheless there is little doubt that the

performance of interface devices, particularly displays, are currently a limiting factor in overall system performance, and that the colour CRT's which are predominantly used have many undesirable features.

Both Paper 29 (presented by J.C.Wright) and Paper 30 (presented by F.deLauzun) described colour liquid-crystal displays. Several advantages were claimed over CRT's, including weight, depth, reliability and ease of maintenance. In spite of problems in obtaining good luminous efficiency, paper 29 claimed that contrast ratio in bright sunlight was better than for CRT's. Possibilities for the future included fault-tolerant and autostereoscopic displays.

Paper 31 by C.K.Lam described the possible use of intelligent controllers to optimise the characteristics of automatic target cuers. The target model is carried in a target correlator and fuzzy logic is used for controlling filter and parameter choices. No results were given.

Paper 32 by H.Hellmuth provided another statement of the man-machine interface problem, in this case in the context of helicopter operation. Equipment becoming available was described, and the use of liquid crystal displays was advocated.

General Comments

The evaluation of each of the sessions given above does not provide an overall assessment of how well the objectives of the Symposium were met, and it is the purpose of this section of the report to provide this additional overview.

It should first be noted that the discussions, limited though they were, did not reveal any significant disagreements on the nature of the problems facing the designers of military aircraft cockpits and interfaces. It was generally agreed that these problems were primarily related to the excessive workload which was experienced by combat aircrew which modern avionics systems had done little to alleviate (and some would claim had actually exacerbated). There was also a general consensus on the range of solutions available (or likely to become available) to designers and on the methodology required to apply them.
It was also quite clear that the topic and theme of the symposium were generally regarded as very pertinent, though the limitation to the machine side of the man-machine interface was regarded by some as a rather artificial constraint, even though a subsequent AGARD symposium was scheduled to cover the other side.

The emphasis of the symposium was quite clearly on two main topics. The first of these was concerned with the overall problem of aircrew management of a highly automated avionics system and the interface implications thereof. There seemed to be a lack of clear understanding by many of the authors of the distinction between needing better interfaces to reduce the workload associated with current types of avionics system and needing new interfaces to reflect the new types of data flow which are necessary for more automated systems which are themselves intended to reduce workload. In this context it was very surprising that no papers were given on the interface aspects of the three programmes specifically intended to provide workload-reducing backup to the crews of single-seat combat aircraft, viz the USA's Pilot Associate, France's Copilote Electronique or the UK's Mission Management Aid. It should also be remarked that the crew workload in a combat or strike aircraft and the optimum design of the corresponding man-machine interface are highly dependant on the characteristics of the weapons being used, yet none of the papers discussed the trends in weapons systems (e.g. their capability for target seeking) and the implications of these for the aircrew.

The second main topic was concerned with the Visual element of the interface, i.e. on displays. Of the 32 papers, no fewer than 13 were directly addressed to this topic. Such heavy emphasis is understandable since the visual channel is the one which has the ability to convey to the aircrew much more information than any of the others. However it has to be said that other important interfaces, particularly those concerned with commands from the crew to the machine, were hardly mentioned.

There was also an overemphasis on the problems of the interface in single-seat combat aircraft which, although understandable in terms of the magnitude of the problems involved, resulted in almost total neglect of multicrew aircraft. It would certainly have been interesting to have had one or two papers on the man machine interface issues in AEW and ASW aircraft and helicopters.

One final comment should be made as part of the technical evaluation. Very few papers gave a description of Research and Development programmes whereas these should surely form the core of any AGARD Symposium. Too many papers were concerned with concepts and possibilities, and although such papers are valuable in their own way, they are no substitute for the hard facts which are contained in a well-written account of work carried out in an R&D Laboratory.

Taken as a whole, the 31 papers which were presented at the Symposium gave to the participants a good picture of the way in which this important technological area is perceived by the experts working in the field. No major technological breakthroughs were described, but rather a steady advance in several areas which, taken together, show some possibilities for overcoming many of the inherent difficulties of the man-machine interface in aircraft. Evaluated against the theme of the Symposium, the objectives were very largely met and the proceedings should stand as a useful record of the state-of-the-art as it currently exists and a pointer to the way in which the interface technology is likely to evolve in the future.

THE ORGANISATION OF THE SYMPOSIUM

The symposium was held in an excellent conference hall, well able to accomodate all the 135 participants, and the projection facilities and simultaneous translation were also very good. The only significant cause for criticism was the fact that less than half of the papers presented were available in written form, even though many of the authors acknowledged that the written papers contained much material that was not included in the oral presentation. The absense of pre-prints which could be studied in advance may also have contributed to the lack of worthwhile discussion following many of the presentations.

WELCOME ADDRESS

by

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Chairman of the Avionics Panel, Symposium Participants, Ladies and Gentlemen,

As Chief of Spanish Defence Staff and subsequently, as Member of the NATO Military Committee, I feel particularly delighted to welcome you to my country and chair this opening ceremony of the scientific sessions that you will hold throughout the week, organized by this important Panel of AGARD.

This is the second time that I have had the honor to open an AGARD Symposium. My first opportunity was in Seville, about one year ago, when the Flight Mechanics Panel of AGARD held a Symposium.

This year, AGARD (founded in 1952 by that unforgettable Scientist, Professor Theodor VON KARMAN), celebrates its fortieth anniversary. Throughout these years AGARD has been and continues to be an extraordinary forum for international cooperation in which scientists of NATO Countries can exchange experiences and work together in scientific meetings on subjects of common interest in the aerospace field and related disciplines.

We can say that AGARD is today one of the most useful NATO Agencies. Spanish participation in AGARD activities has follow an increasing role. The number of Spanish professionals taking an active part in these activities is growing, either as Panel Members, or Members in Working Groups, or Authors. At the same time we are increasing the rate at which we host AGARD activities. In 1992, for example, we shall hold here, besides this Symposium, two Lecture Series, organized by the Aerospace Medicine Panel and Guidance Control Panel. This does not consider the various consultants missions and Working Group Meetings affiliated with Spain.

I want to take advantage of this occasion to thank General BAUTISTA for his outstanding work for AGARD for the 4 past years. Up until his recent retirement he served as s Spanish National Delegate to AGARD. At the same time I would like to congratulate General GUITART, nominated as new National Delegate, who I know, will continue this fostering cooperation mission, with enthusiastic dedication.

Changes in the World's political situation, especially the changes in the former Soviet Union, the abolishment of Warsaw Pact, and the political status in the communist Eastern Europe Countries, the reunification of Germany, etc. have caused a somewhat relaxed military posture that, in spite of persistent small conflicts and areas of latent crisis, has driven NATO and its Member Nations to a decrease in their military commitment and budgets.

We hope, that these budget cuts will not affect AGARD resources and therefore AGARD activities. Research and Development in the aerospace field has a beneficial impact in many other areas of science and technology.

The results of these advances in technology are only realized in a long range evaluation. R & D efforts cannot be slowed as cuts in these areas can cause long range problems.

The subject of the Symposium to be opened today is "Advanced Aircraft Interfaces: The Machine Side of the man-Machine Interface. This is not easily translated in Spanish but we could say : El Lado Maquina en la Tecnologia de la Relacion Hombre-Maquina en los Nuevos Aviones.

The extreme interest of this subject is focused in the growing complexity of the modern Air-Land Battle. This places a large workload on the pilot and crew of combat aircraft. Nevertheless, new technologies, offer potential solutions to most problems resulting from these increased workloads.

The 32 papers to be presented here appear to be to be extremely promising and attest to the high professional qualities of the lecturers.

I am sure that this meeting will result in a most profitable event for everyone.

I want to transmit my best wishes for a successful meeting and also a very pleasant stay in Madrid.

Ladies, Gentlemen, welcome to this Symposium..

Thank you.

KEYNOTE ADDRESS

by

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Managing Director
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Chairman, ladies and gentlemen,

It is a great pleasure and honour to be given the opportunity to address this distinguished attendance to the AGARD Symposium on Advanced Aircraft Man Machine Interfaces, with emphasis on the machine side of the interface.

This is the first Symposium of the Avionics Panel in Spain, and it happens in a year that Spaniards have come to think as a Wonder Year, since we have Universal Expo in Sevilla, we have the Olympics and Madrid is the Cultural Capital of Europe.

It is indeed a honour because I believe Aircraft Man Machine Interfacing is one of the most important and creative challenges, of technology today. I have to say that not everybody in the aerospace industry gives adequate regard to this topic, and some think that falls within the superfluous good-to-have items brought around with the requirement for computers. I am sure this views are rapidly disappearing.

What is one of the fundamental problems associated with airborne man-machine interfaces?

The modern high performance military aircraft or helicopter is the result of very fast development, instated by the actual or estimated threat of potential adversaries. It is now the basic element of a very sophisticated weapon system in the hands of the pilot, with tremendous firepower, very fast and agile.

The pilot, as a human being, is a marvel of physical adaptation to walking on two feet at low speeds, on the surface of the earth, mostly in daylight. Over centuries he has been a hunter, and his vision, audition, smelling, and kinestesic senses have evolved to make him effective and also to allow his self protection, in the natural hunting environment.

The skills to survive in our highly competitive world, be it at war or in peace, are determined by evolution of his mental abilities and not his physical or strictly sensory qualities.

We can, and do, struggle to analyze and understand how humans behave, perceive, learn and perform missions or tasks. We can conceive training processes but we cannot change natural limits.

So the fundamental problem is to adapt the aircraft system so that it provides a viable interface to the real pilot under the extremely varying environments in which he has to perform, including night or day, adverse weather effects, and extreme mission requirements and threat intensity, with acceptable levels of safety and mission success.

This problem has received in the last 15 years increasing attention and this Symposium and others that have taken place, and are to be held by AGARD in the next future, show this.

It is, perhaps, not peculiar to aircraft, but the distinctive characteristic of the fast timing give it a different dimension.

It is moreover a reality that the problem remains unsolved and some review of the facts about military aircraft non-combat losses in recent crises and exercises show the urgency and the extent of the effort to be done, if present day military aircraft are to cope with Air Staff mission

specifications. (Note that modern commercial aircraft losses should add to the concerns).

When we compare the incidents and accidents derived from structural, engine or avionics failures with those generated by human errors or Human Factors failures, the picture is really a grey one for the contribution of this technology to safety and efficiency.

I want to recall a statement of the Lt. Cnel Simonsen of the RDAF at the AGARD Lecture on Visual Effects of the High Performance Cockpit: "We have probably not seen one single type of aircraft without at least one major human factors design deficiency".

So let me say as a first remark that the subject of the conference during these days is a very acute problem and a very important one in terms of life risk and mission success.

<u>* The workload problem.</u>

But is it really so complex a problem?? Is it not just ergonomics and space allocation in the cockpit?? Our answer is the subject has indeed great complexity.

The military relevance of aircraft weapon systems make them the target of an impressive concentration of ground and air threats. The pressure for more and more sophisticated weapon system features and capabilities, reflect ultimately in pressure on the pilot performance, as operator of the aircraft <u>and</u> the system.

This typically results in tasks of the pilot that combine

- Tactical Decision Making and Tactical Situation Assessment, obviously <u>at combat speeds</u> and in three dimensions, continuous tactical planning and replanning and action execution.

- Sensor management, Sensor Selection, and data assesment and weighting.

- Vigilance and Search; Detection, Recognition, Identification of expected or unexpected targets or threats or events.

- Monitoring the aircraft systems for proper functioning.

- Control, either mediated or direct, of the aircraft, and weapons.

- Communications with formation or command.

Depending on the mission and mission phase this workload is or can be largely incompatible with pilot performance capabilities, and leads to potential <u>break down</u> specially when coupled with adverse sensory conditions, physical stress and spatial disorientation.

What can be done ?? It is clear that basic elements of the solution are Cockpit automation and Pilot computer aiding in order to relieve some of this workload, in new aircraft designs but also in older aircraft, through modernization, if the actual environment in which they are used was not considered in their design.

The underlying Man-machine interface technology is just <u>emerging</u> today with major improvement underway at <u>System, Subsystem and Device Levels, which will be mentioned later.</u>

<u>* The human side of the Interface.</u>

But let us not forget that we are talking <u>interfacing</u>. We need to think for some minutes about the other side of the interface!.

All the improvements have to be derived, in any case, from an <u>understanding of human skilled behavior</u> and how it is organized in pilot performance.

From a System point of view the human operator has Sensors such as Visual and Auditive, effectors such as Voice or Hand, and a Information Processor where mental behavior is provided.

The Human Information Processor can be represented simplistically as structured around a large, relatively slow access, long term memory, and three processing elements: a Perceptual Processor, a Motor Processor, and a cognitive Processor, all working, on a fast access and small size <u>short term memory</u> that is the <u>working memory</u>, which is linked under cognitive processor control to long term memory, this working memory being linked under perceptive processor control to sensors.

The processors have a characteristic time on the order to 100 msec, and working memory has a typical volatility period of about half minute.

The Sensor and Processor model allows us to rationalize on the basic known facts that human operator activity is limited by physical sensor configuration (visual, auditory, tactile) and processing capability, data set size and throughput, but within those limit has multitask capability.

Skill acquisition and execution is the basic tool of man adaptation to the increasingly demanding tasks that he is requested to perform, and allows fast and efficient reaction.

It is more difficult to model in a simple way the role of skill acquisition and how skilled performance is actually executed, but it can be visualized as a very efficient way to retrieve or access large pieces of information such as data, procedures, or methods from long term memory by using associative mechanisms generated by experience and training.

Skilled Human operators are capable of handling complex tasks.

For example in the case of a continuous control tasks, when the order of the system to be controlled is high and the characteristic frequencies are too high, the skilled operator generates a virtual reduced order model that he is able to control within the processing throughput limits and generally achieves stable control with reduced accuracy.

In sequential tasks when working memory requirements are excessive he skilled operator tends to break down the whole task in unit tasks so that, the memory requirements can be fulfilled.

Unit task decomposition is at the very root of the skill adquision cycle. Just remember how people used to perform by hand arithmetic divisions by breaking down the total task (the full number to be divided) in smaller ones and writing down the intermediate results so that the next step could be done. If you visualize this example you realize the conditions for unit task decomposition that are

. Working Memory Capacity for each step.

. Information Horizons
Data: What you see is what you need.
Method: What to do each step.
Task: What boundaries, input and output

. Error Control.

Skill acquisition provides for the evolution of human mental behaviour through its skill dimension.

At its origin there is the pure problem -solving behavior characteristic of new/ improve situations where man makes trial and error steps in order to achieve a goal that he has set. With experience and training he travels along this dimension gaining skill, that is, developing strategy, methodology, and ultimately memory. Depending on the task nature, environment, and timing and memory requirements extreme skill can be developed with automaticity or the behavior remains a problem-solving one, or what is the most usual case, the task is broken down into several subtasks falling each one into either category.

Problem-Solving behaviour even if slow is what makes man's contribution essential.

Having said all that about the other side of the man machine interface, what is it possible to do on the machine side to reduce multiple task workload?

I would say actions can be categorized into task design "optimization for sharing" and pure automation.

* Task design.

About task design four clear directions should be pointed.

First is task resource demands reduction by improving those task characteristics that are most resource demanding, like for example:

Sensory
. Visual clutter and display resolution
. Readability of symbology.
. Auditory display clarity.
. Auditory display noise.
. Tactile smoothness and feedback.

Processing

- Memory retention duration and size.
- Phonetic and semantic confusability.
- Response Frequency and Complexity.
- Degree of choice.

Motor

- Stimulations-Response Incompability.
- Error intolerance and accuracy requirement.

Overall

- Controlled system order and bandwidth.
- Control gain.
- Tolerable delay

A second element is to facilitate task parallel processing by using for concurrent tasks, wherever possible, separate channels at the sensory, processing and motor stages. Therefore task design should take advantage of shareability of

- Peripheral modes
    - Auditory vs. Visual Perception
    - Voice vs. Manual Control
- Encoding
    - Verbal vs. Spatial Encoding
- Processing
    - Perceptual Cognitive vs. Perceptual Motor.

Third is task synergy and integration.

Synergy can be exploited at sensory, and control levels by concentrating visual inputs that may have to be perceived concurrently like for example is done with target and own aircraft data in helmet mounted displays.

In this case display information of various origins in a way that leads to integrated processing can be very effective load reduction device.

Finally one of the most effective task design techniques is to define and appropriately support task decomposition into unit tasks.

<u>* Cockpit automation.</u>

In the cockpit we find initially three different kinds of automation: <u>Control Automation</u> such as autopilots and flight Management Systems; <u>Detection Automation</u> including topics like Sensor fusion but also alert and warning generation; and <u>Decision and Assessment Automation</u> that includes decision aiding, situation assessment and diagnosis.

The problem of replacing human performance versus assisting, and how, the human operator is a difficult one.

Generally speaking if we look at the continuous dimension of problem-solving/skilled behavior or knowledge based versus rule based performance it is clear that an activity that human can perform based on pure skill can be automated. There are little number of those at the higher levels of complexity and interactivity, typical of the unpredictable combat environment but clearly progress has been done, and there is still ample room for additional automation.

On the other hand automated systems can become complex and therefore complicated to set up and operate without critical risk of error. So in many cases automation is to be partial, for certain subtasks of a whole, and therefore requires abstract man machine interaction.

Such interaction has been implemented through the ubiquitous use of the CRT screens and multifunction displays, and will probably extend into "Big picture" and helmet mounted displays, with possibly increasing use of voice-auditory commands and inputs.

Whatever the physical interaction medium, the type and format of the symbology, either verbal or spatial, remains a key issue associated with decluttering, scheduling, and the difficult topic of supervisory control acceptance by the pilot.

<u>* Adaptive Automation.</u>

A word should be said about Adaptive Automation and Interfacing, dealing with system in which the degree of automation is tailored to he varying needs of the pilot or human operator.

Do we know what the pilot thinks or needs?. Adaptation to the individual requires to identify the cognitive state of the human and devise at every point in time what he needs; and supply that help,

and only that. For instance analyzing eye fixation can give information on what the pilot has remarked and allow to supply related information.

Adaptation to the situation or the external circumstance requires to identify such situation and provide the type of automation and information display that is best suited for it. This is increasingly being used through automatic moding and context detection.

System Instability and system failure recovery are areas to research and solve.

<u>* Conclusion.</u>

As conclusion, man with all his physical and functional limitations, with error making and disorientation tendencies, with attention failures and sensory and psychological inadaptation is the one necessary piece of the military aircraft and the key to its combat superiority.

Task design and automation should always be directed towards aiding such limitations and allowing maximum use of his capabilities.

I have tried to introduce some key topics of the subject and I hope, ladies an gentlemen, that you have an interesting symposium and a nice stay in Madrid.

ENGINEERING THE VISIBILITY OF SMALL FEATURES ON ELECTRONIC FLIGHT DISPLAYS

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Keywords: electronic displays, flight imagery, visibility.

SUMMARY

The applications and limitations of high resolution afforded by modern display technologies are discussed, in relation to the properties of the human visual system; and how much 'engineering' may become possible early in the design phase by the use of model(s) of the 'visual system - technology interface' (VSTI). Display technology models provide good predictions of the distributions of luminance, color and contrast under specified driving and environmental conditions. Coupled to suitable vision models, estimates of visibility of pattern details can be made.

In VSTI models, the beholder of the imagery is regarded as a detector responding to displayed patterns with 'yes', 'no' or even be allowed fuzzy and false responses. Some conclusions are given concerning design of pattern details in imagery, given the characteristics of the display and of the observer.

LIST OF SYMBOLS AND ABBREVIATIONS

A	apparent area of observed object
B	brightness
ΔB	brightness interval
C_r	contrast ratio: foreground luminance L_f over background luminance L_b
D	area of (eye) pupil
L	luminance, luminous flux per solid angle and per surface area [nit]
ΔL	luminance difference
m	modulation index
p	pitch of display elements
P	active area in % of display element
σ	standard deviation of distribution
t	time, time duration
v	visibility
x,y	spatial variables at the display face

CRT	cathode ray tube
del	display element
EL	electro luminescence
JND	just noticeable difference
LC	liquid crystal
LED	light emitting diode
MMI	man machine interface
pel	picture element (also pixel)
PSF	point spread function
VSTI	visual system - technology interface
2-D	variables extending in 2 dimensions

1 INTRODUCTION

The combination of digital electronics and new display technologies offer programmable high resolution, color display devices: Head Down, Head Up, Helmet Mounted, Wide Field of View, Super Imposed, etcetera. Power consumption is very moderate; weight low compared to the performance; thermal and electromagnetic radiation passable. Advanced graphics and image processing software afford new creative opportunities in imagery design, with strong appeal to man's inborn cognitive abilities.

Fast perception of *information* (in contrast to raw data) is the issue.
We now see more 'natural' coding in the man-machine-interface (MMI): improved matching of the 'problem data' formats to the style of human 'inner representation' (geometries and contrasts with very good cognitive characteristics, identifiers such as generally valid geometry rules, color, positions, pattern labels); and by 'fooling the eye' through adaption of the spatial and metrical features of stimuli (like the OCR font was designed for machine vision) to the operative states of the 'parameters' of the vision system, induced by the existing environmental conditions.

Fast and reliable acquisition of image data at low probabilities of confusion requires that the brain be presented with 'adequate' pattern stimuli. Important is **visibility** v, here defined as the probability that the eye receives sufficient luminous energies to send 'adequate' signals to the brain. Factors involved are: luminance L and integration time t; pupil diameter D; apparent size A of the object and local spatial contrast distribution $C_r(x,y)$ to exceed thresholds of seeing.
Low visibility takes time.

How fine should be the displayed 'artwork'?
Consider rather intelligent machines able to calculate the success probabilities of a choice of operations, in the order of their priorities; and advising the pilot accordingly. It is conceivable that the messages of such a machine do not need very high resolution, in contrast to imagery in the current situation where all the intelligence is concentrated in the pilot. Thus, expensive machine 'intelligence' can probably be traded for the considerable cost of (often only locally required) high resolution in large surface area displays.
For the time being the driving forces in display R&D are towards large, adaptive, large contrast range, color displays with high resolution.

Good visibility is required for both the "written" features of a symbol and for the "empty" or "nonwritten" spaces in between. Easily confused image features share similarity factors (both cognitive and psychophysical) with the desired feature. It depends on the distances in the feature space whether false responses, i.e. pattern confusions, occur. Optimal use of cognition is a matter of image design, not of display technology. Therefore, our analysis is restricted to high probability of detection and, to keep matters relatively simple, to the effect of brightness only.

Complicated images are formed by local combinations of elementary patterns which, in turn, are made up of dels.
Gray levels are used for several reasons:

- to attract attention or, inversely, to normalize brightness of differing colors;
- to fool the eye into seeing smooth lines, sub-del edge displacements and varying line thickness;
- to normalize the perception of subtle pattern features.

But in many cases the combined requirements on contrast and luminance ranges (gray levels, dimming; good visibility under all circumstances, little glare, no blinding) often are difficult to satisfy, unless the imagery is designed for robustness.
The inverse solution would be to control visibility by excluding changes in VSTI conditions, like in the windowless cockpit. Then, and even at moderate cost, every refinement is possible in visual transfer of information (but also necessary!): and large panel area and high resolution and a wide color gamut.

Perceived image quality is neither assured by global technical specifications of the display technology or the specific product, nor by general ergonomic considerations applied in the design phase of the display. In particular, the **visibility** of displayed patterns depends on geometries, on very local contrast and color differences and on the adaptation state of the eye.
In terms of detector models: sufficient changes in local brightness and color to be detected with high probability, e.g. >99 %. Low probability of confusion needs adequate visibility of the individual features. Therefore, it is necessary to study the factors determining visibility of local pattern details. In table I the factors in some way affecting visibility are marked. In this paper the focus is on: average brightness, line separation, stroke width, active area and blur.

TABLE I: VISIBILITY FACTORS

- Del active area
- Del-to-del luminance contrast
- Quantisation; contouring
- Brightness ripple
- Whole image vibration
- Line jumping due to interlace
- Del-to-del color contrast
- Separation gap width
- Del/gap luminance and color contrast
- Line spacing
- Stroke width
- Symbol area
- Intra-symbol area
- Symbol spacing
- Reflections
- Average luminance
- Dimmability
- Adaptation state of the eye
- Dwell time of fixation (short/gaze)
- Flicker (global and local)
- Blur
- Noise
- Shading

- Task dependent factors

2 BRIGHTNESS

2.1 From luminance contrast to brightness

Brightness B, not luminance L, determines the quality of perception. The definition of visibility v can be redefined as the probability that the accumulated photon fluxes in the pattern spatial distribution L(x,y), received during a given time interval t (dwell time of 1 fixation, see figure 1), produce brightness changes ΔB in the resulting brightness distribution B(x,y) sufficiently strong to to enable interpretation by the brain.

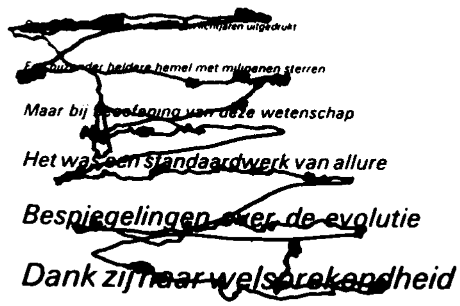


Fig. 1) Example of visual scanning of text: fixations (dwell time > 0.25 s) and saccades in between (< 3 rad/s)

The number of photons raining on the retina depends on the variables A,L,D,t. The brightness changes ΔB are modeled by two separable functions: $\Delta B = f(A,L,D,t).g(C_r)$ with $0< f(A,L,D,t) <1$.
The target apparent area determines not only the number of photons exiting from the surface, but also the contrast loss due to point spreading in the optical part of the eye (smearing, reduces the number of photons at the axis of viewing). This loss is partly restored by neural action in the retinal tissue. Thus the spatial brightness distribution ΔB(x,y) of the pattern results from its luminance distribution L(x,y) by a mapping in early visual processing.

Perceived sensation of luminous contrast is rated by counting the number of threshold brightness increments (JNDs, for which by definition $\Delta B = 1$) which fit in the interval ΔB associated with the luminous contrast.
The JND is measured e.g. as a 50 % response probability to the luminance change. This response level is also chosen for the 'visibility' $v(\Delta B= 1)$ (threshold of seeing).
Blackwell (1946), measuring the JND using disc shaped targets, found the threshold visual contrast $\Delta L/L = 0.0027$ over wide ranges of disc diameters and luminance, in agreement with Weber's law: $\Delta L/L$ is constant. Systematic departure is experienced at small target area, low light conditions, short exposure.
Weber's law suggests a logarithmic function coupling brightness to luminance; regional

$$\Delta B \approx 370.\ln C_r .f(A,L_b,D,t). \qquad (2.1)$$

2.2 Visibility

Visibility v is a saturating function: the wide range of the brightness interval scale is non-linearly mapped onto a visibility range of $0 < v < 1$.
For long (many eye PSFs involved) edges, separating two uniform fields, this mapping can be modelled by the error function:

$$\mathrm{erf}\ u = 2/\sqrt{\pi} \int_0^u \exp(-t^2).dt.$$

Remembering that the visibility at $\Delta B = 1$ equals 50 %, the model for the visibility v associated with brightness interval ΔB is:

$$v = \mathrm{erf}\ (0.48\ \mathrm{Int}|\Delta B|) \qquad (2.2)$$

For ΔB = 3 JND, v already attains 0.96.
Figure 2 combines the variables luminance, brightness and visibility. Depicted are:

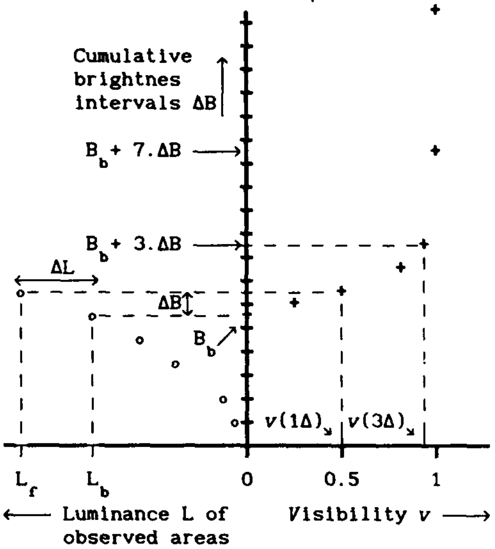


Fig. 2) Mapping of luminance contrast via brightness intervals into probability of seeing that contrast

- To each increment ΔB = 1 JND corresponds a ratio $\Delta L/L_b$ (Weber's law), provided the average luminance is sufficient (photopic range, not photon noise-limited).
- The 'zero' of the brightness/visibility function shifts to the brightness level corresponding with the background luminance L_b.

The parameters object area, pupil size and dwell time in $f(A,L_b,D,t)$ are omitted; likewise the 'adaptation state of the eye'.

But for small objects (local regions in the image, e.g. small discs, triangles, bars) the threshold ratio $\Delta L/L_b$ is not invariant; on top of the effect of received photon energies it is also a function of the geometry because of locally operating 'lateral inhibition', a neural contrast enhancement process on the receptor outputs.
In complicated patterns (such as in flight symbology and text) the perceived local contrast thus depends on size/area of the patterns/features, **visibility analysis must be based on (2-D) brightness distribution calculations**, using an engineering model of vision describing early visual processing in the eye.
Therefore the statement by Galves & Brun (1976), that for visibility assurance at least 7 JNDs are required ($\Delta B > 7$ threshold brightness increments: $C_r > 1.02$) is not sufficiently precise. Also it is not valid at the very low end of the photonic range into the scotopic range where every photon counts (should be counted by the receptors in the retina); where nature invokes energy preserving additional processes.

The appearance of the images presented by display devices also depends on the chosen technology; consequently the visibility of pattern details also. We arrive at the computation structure of figure 3. The remainder of the paper focuses on the third part: the vision model.

2.3 A vision model

The eye is modeled as an early visual processor, responding to local contrasts by corresponding numbers of equal brightness

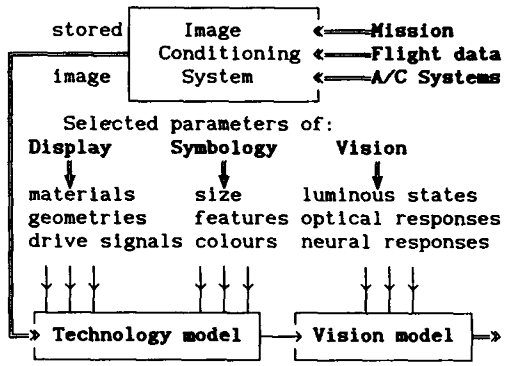


Fig. 3) Modeling the visibility of images displayed in a specified technology

increments allowed to also produce false responses. In figure 4, one possible engineering model is depicted (Bakker and Bosman, 1988).
It is composed of:
- an optical part, representing the eye optical system, accounting for aberration of the lens, pupil diffraction and scatter in the mess of nerve bundles and blood vessels just in front of the retina; the result being smearing of the input image.
- a detector part, representing the eye neural system which resolves the smeared illuminance distribution at the retina into 'sharp' brightness signals sent to the brain, taking account of photon noise and neural noise.

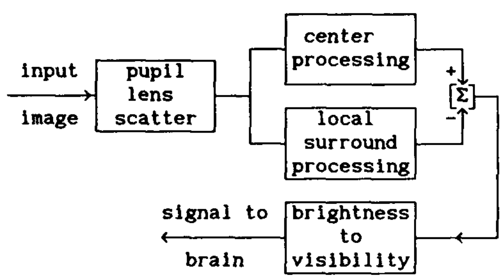


Fig. 4) The blockdiagram of the vision model

The detector part consists of two branches, with different smearing properties (center with low smearing, surround with strong smearing); both perform a log operation.
All 'Point Spread Functions' (PSFs) involved are not invariant but depend on internal states and environmental luminous conditions.

Note that the log operation followed by subtraction of the two 2-D images yields a brightness interval 2-D distribution proportional to the luminance contrast ratio distribution; while simultaneously performing enhancement because the (wide) skirt of the optical PSF is removed by the lower branch PSF (known in image processing by the name 'unsharp masking', in vision literature as 'lateral inhibition'.

Photons available in a point source are distributed by a PSF to fill its entire volume (Westheimer G. & Campbell F.W. 1962), thereby lowering peak response considerably. For the eye optical PSF_{op} its peak magnitude is attenuated 70 times with respect to absence of smearing.
A large area stimulus is composed of many points, their overlapping responses add their photon catches to produce a uniform response close to unity.
The responses of the eye optical system (transfer function from object to retina) to several pattern primitives are depicted in figure 5.

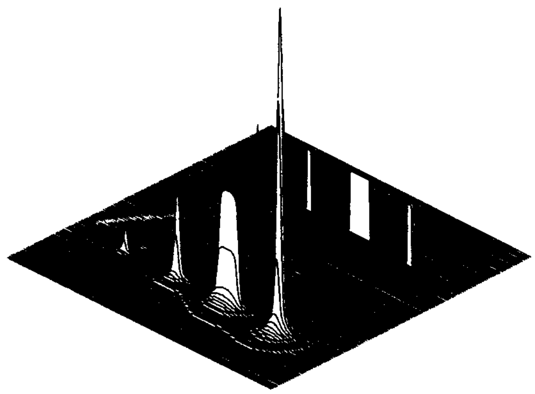


Fig. 5) responses at the retina (receptor level) of the eye optical system
a) a point source (PSF_{op});
b) a linepiece, very thin, with length 5 times the width of PSF_{op};
c) a long line; and
d) square stimulus of 5×5 widths of PSF_{op}.
(Note the differences in peak magnitude)

The spatial response of the total model to a point stimulus (eye PSF) (Blommaert and Roufs, 1981) is depicted in figure 6c), along with the PSFs of the foreground path (6a) and the background path (6b) (neural pooling PSFs located in the detector part of the model). This response is taken to be valid in the center of the foveal region (foveola).

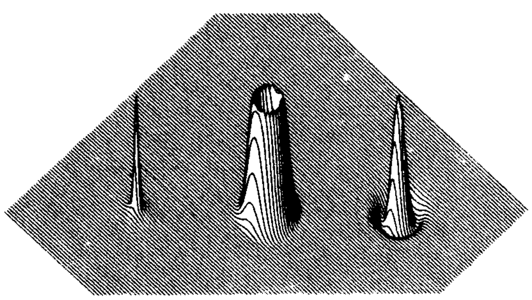


Fig. 6): Point Spread Functions in the vision model, see text

A small target, like an alphanumeric character of 6 mm high seen at 0.7 m, has a viewing angle of 30 minutes, well within the size of the foveola where the retinal resolution remains about invariant. The operation of the model (optical smearing, lateral inhibition and mapping from luminance to brightness) is demonstrated in figure 7, showing the letter 'A' as it appears on an electro-luminescnce display and the perception of brightness.

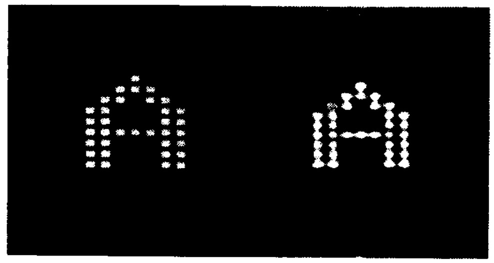


Fig. 7) Mapping luminance into brightness by the vision model.

Towards the periphery the PSF aequivalent cross section increases (Koenderink & van Doorn, 1978). In figure 8 the gradual loss of sharpness (and contrast) (one fixation) in peripheral view is demonstrated. By taking several fixations across the image the brain builds up a total sharp picture. Moreover, memory from previous (almost identical) views are thought to reduce the required number of fixations.

Fig. 8) Loss of sharpness away from the point of regard.

2.4 Quantitative examples

For non noise-limited conditions (luminance > 10 nit) the combined effect of variations in luminance, fixation time and pupil diameter is small. The response in number of JNDs can be approximated by

$$\Delta B \approx 370.\ln C_r.f(A), \qquad (2.3)$$

with f(A) a function of e.g. the area and shape of the stimulus. One obtains $\Delta B \approx 7$ JND (≈ 100 % reliable detection) for large area objects ($f(A) \approx 1$) at a C of 1.02. **BUT**, for small stimuli like a short bar, i.e. a linear array of 5 display elements (figure 5b) at the (high) resolution of 12 dels/mm, the eye PSF_{op} attenuates the input contrast ratio of 1.02 to 1.0026 at the retina; its brightness interval ΔB equal to 1 JND! Fine detail is barely visible. **Such an image looks ghostly.** In figure 9 the visibility is plotted of the 5×1 bar as function of display element size.
It is clear that, at higher resolutions or in finer artwork, the display must be driven harder (more contrast required).

To see also points (i.e. very small dels) reliably, the contrast ratio must be $C = 1 + 70 \times 0.02 = 1.4$!
In gray scale images these considerations are valid at all (local) background levels; thus without 'fooling the eye', gray scales should have contrast ratio intervals of minimally 1.4, in agreement with earlier evidence (Carel 1965).

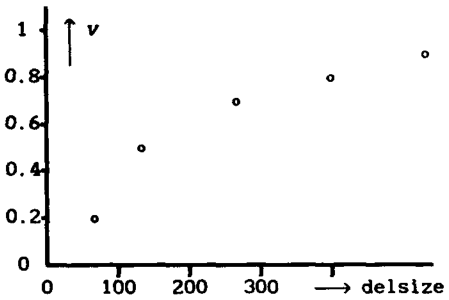


Fig. 9) Visibility versus size of the display element in μm for a bar 5 dels long and 1 del wide. Viewing distance: 0.7 m; Contrast ratio: 1.02; background luminance: 100 cd.mm^{-2}.

This leads to excessively large luminance ranges (> 250, in addition to the required dimmability range). Again compensation can be found either in driving the display elements adaptively, or in special designs of 'small' feature areas while retaining full resolution to preserve image quality.

Decreasing the viewing distance increases angular size, which diminishes optical attenuation, thereby increasing contrast at the retina. Moreover, at higher luminances more photons partake in the stimulation process so that the neural PSF control can decrease the aequivalent cross section resulting in a crisper picture.

The desire to augment the visibility of very small features relates to the reason why people tend to bend forward and/or to operate emissive displays at higher luminances.

In radiant stimuli with strokes made up of several dels, visibility is much higher due to 2-D merging of PSF responses. Assuming ample contrast (ΔB ≈ 25 JND) The *effect of* stroke width is depicted in figure 10, consistent with (Reger & Snyder & Farley, 1989) for 9x12 matrix blocks or better.
At reduced angular symbol height, the smallest intra-symbol spaces (in 'a' and '8') with area < 2' experience loss of visibility. The same happens when stroke width increases at constant character height, implying that the curve of figure 8 mirrors at thicker stroke widths.
At positive contrast effects of PSF merging is detrimental for very thin darker strokes and for intra-symbol spaces. contrast of the whole symbol suffers, not only certain features.

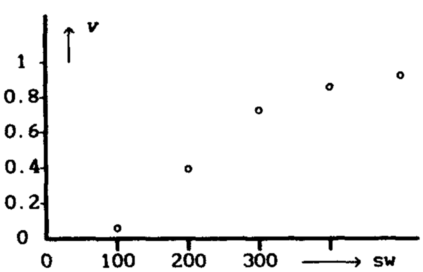


Fig. 10) Visibility *v* versus stroke width sw in μm. Viewing distance 0.7 m

Some Avionics displays use light emitting diodes, providing very thin lines at high brightness. That the visibility of very small gaps in LED arrays is high, is calculated as shown in figure 11, which depicts the required brightness in JND as function of gap width. Consequently, from the visibility angle, character height can be quite small.

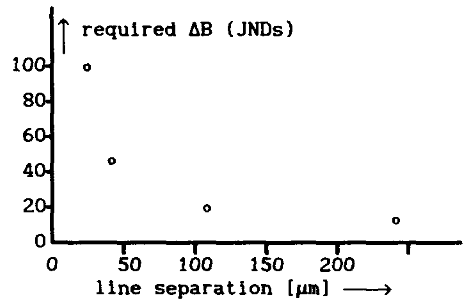


Fig. 11) Threshold brightness of gaps 0.7 m viewing distance

3 LOCAL BRIGHTNESS MODULATION; EFFECT OF ACTIVE AREA OF THE DISPLAY ELEMENT

3.1 Modulation of pattern features

At lower resolutions the individual display elements remain visible, causing modulation of the pattern features shown in figure 12. The subtraction operation in the model of figure 4 is responsible for 'lateral inhibition' producing 'Mach bands' (the trough around the peak in figure 6c). In figures 12 & 13 its effect on a complicated *shape* are depicted.

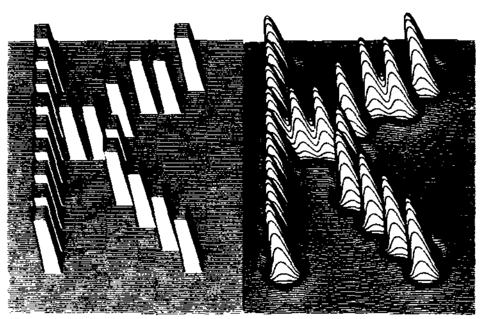


Fig. 12) Response of low resolution display with separation gaps between the display elements. Delpitch ≈ 500 μm.

Consequently (see also figure 7):

A) 'small' square display elements seem rounded instead of square; separation gaps widen at the intersections increasing their visibility.
B) with uniformly driven display elements, the ones with few neighbours (e.g. the upper del of the letter 'A') are seen at increased brightness, thus seem larger than the ones surrounded by many neighbours;
C) the inhibitory lateral action produces also local contrast augmentation around the features of the pattern.

To calculate the modulation index, it is necessary to use the 2-D vision model. By the same means it is possible to design reduction of image-dependent unwanted modulation, using gray level blurring techniques discussed in section 4 below.

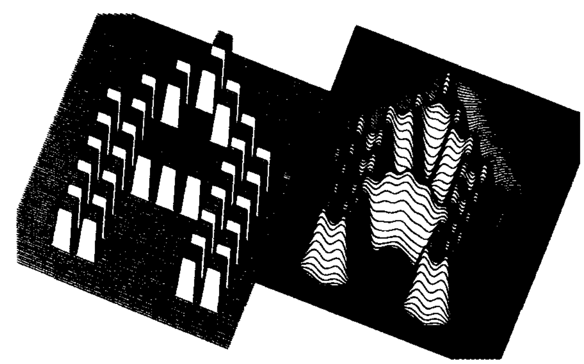


Fig. 13) a) the 3-D luminance distribution of a symbol A at the face of a EL display with separation gaps of 1/3 of the pitch;
b) the corresponding brightness distribution of the same symbol, obtained by the model, when the symbol height is 4.5 mm viewed at a distance of 0.7 m.

A reasonable model to estimate modulation contrast in the brightness pattern of adjacent dels of a line in a main direction of the display is the expression:

$$m = \exp\left\{ - \frac{\pi\sigma^2}{(1-P)(p+\sigma)^2} \cdot \frac{P(p+\sigma)^2 + \pi\sigma^2}{(p+\sigma)^2 + \pi\sigma^2} \right\} \quad (5.1)$$

the modulation index $m = (B_p - B_s)/(B_p + B_s)$;
B_p: peak brightness, B_s: saddle brightness
σ the s.d. of the eye PSF.
A plot of m as function of p/σ with parameter P is depicted in figure 14.

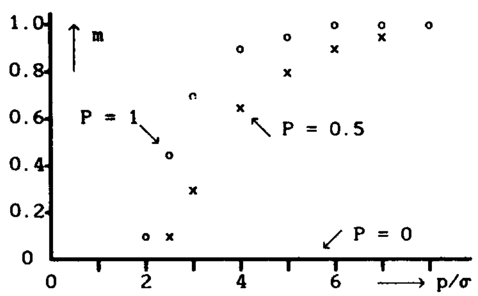


Fig.14) Effect of pitch, active area and eye PSF on brightness modulation

3.2 The effective area of a display element

The ANSI standard for Human Factors Engineering of Visual Display Terminal Workstations states that the minimum permissable active area or fill factor in flat panel displays be 30 %, preferred is 75 % . From the foregoing it is obvious that resulting brightness modulation varies with del size and pitch. The recommendation thus is not sufficient in itself; some function of both the number of elements in the character matrix and the active area per del should be considered.
The resulting brightness modulation then depends on the adaptation state of the eye. One may specify a fixed 'standard' eye PSF or use the brightness model to calculate the resulting modulation. Based on the assumptions of the model, under good viewing conditions the modulation seems secondary as it hardly affects visibility; only deep modulations are thought to have effect but this should be verified.
Active del area convolves with the eye PSF, producing a modified PSF with effective area about equal to the sum of both. E.g. like in figure 12, with del pitch of 2' and eye PSF with effective area of 1.5' solid angle, the 45 % active del area results in a PSF with effective area of 3.4' solid angle. The modulation contrast is clearly visible in the brightness pattern of dels in a line in a main direction of the display. With 75 % active del area the resulting effective area becomes 4.5', larger than the pitch squared (overlap). For that reason modulation contrast is only visible in oblique lines.
These considerations determine the required resolution for uniformity of brightness.

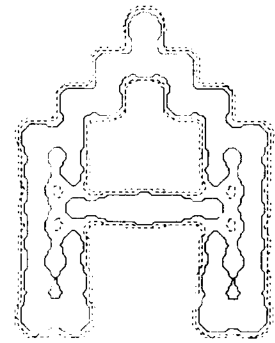


Fig. 15) Iso-brightness contours at
a) 1 JND -outer/dashed,
b) 3 JND -inner dashed and
c) 7 JND -solid line.
Geometry of figure 12, C_r: 1.4; L_b: 100 nit.

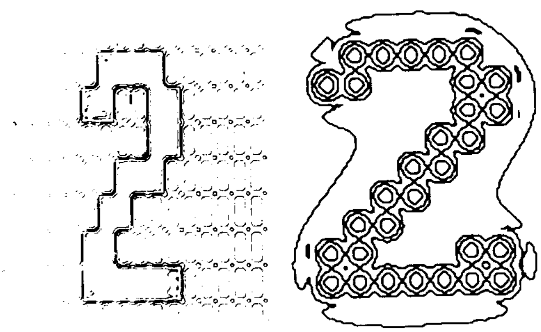


Fig. 16) Display iso-brightness contours:
a) electroluminescence,
b) twisted nematic LC, backlighted

The effects can be studied by plotting iso-brightness contours as shown in figure 15. The contour at 3 JND of 15b) determines the perceived contour of the symbol. Note modulation due to insufficient merging of PSFs.
Annoying? Who knows.
Figure 16 shows the iso-brightness contour families of symbols and background (7 JND) on two commercial displays.

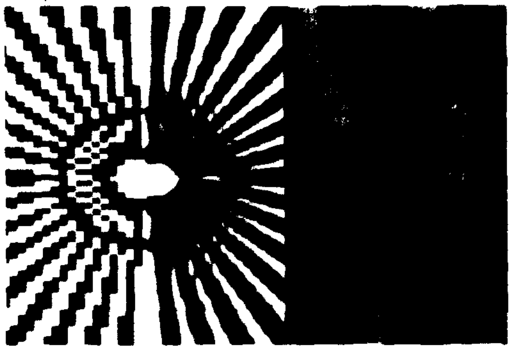
4 EFFECT OF BLUR

Blurring (spatial low pass filtering) occurs through smearing of the designed image with a point spread function situated either inside or outside the eye. Examples of 'inside' blurring are given in figures 6 and 8. It also occurs (much stronger) in neural pooling of receptor outputs at low

light levels when necessary to lift the total photon catch to exceed the neural noise threshold. 'Outside' optical blurring occurs unwillingly at the screen of a CRT or in display cover layers and antiglare filters, or on purpose by electronic and/or algorithmic means.

Blur causes additional gray levels. Unwanted blur is most bothersome in sharp turns of lines; and it narrows intra-symbol spacing, where it should be avoided. Hamerly & Dvorak (1981) pointed out that edge gradient softening by 0.4' in normal print causes the experience of bold print.

In low to medium resolution quantised displays blur can actually improve the perception. In figure 17 two approaches are shown: a) by 2-D linear interpolation (Bosman & Umbach, 1982), b) by adding extra graylevels in the direction of the line (image dependent 1-D interpolation, Negroponte, 1980).



a) b)

Fig. 17) Removal of 'jaggies' by
a) 2-D linear interpolation
b) 1-D interp. along the line.

suggesting a resolution of 0.5'. But the circular symmetric eye PSF with effective area of 1.5' solid angle attenuates fine 2-D detail. The cut-off in resolution (single fixation) can be expected at about 2' per del (2.2 dels/mm at 0.78 m viewing distance). At higher resolutions wider 2-D excursions and/or higher contrasts are necessary to be perceived in the same time slot. Correlations between gray levels of display elements in patterns are image dependent and must be individually defined in each symbol matrix.
Such intended 'blur' operations, being nonlinear, can be determined with the aid of the calculated spatial brightness distribution, or determined in interactive experiments.

5 CONCLUSION

Visibility limitations occur in early visual processing and are very local. The usual display specifications involving several degrees of viewing (!) describe only global characteristics; they cannot predict perceived symbol display quality. Such parameters either must be measured by ergonomic experiments or can, with limited accuracy, be predicted by an engineering model of vision as argued in this paper. Judged by the results of our research, the parameters currently used to define display standards (technology and imagery) are *less suitable to enforce display quality in the sense of good perception.*

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HUMAN FACTORS PROBLEMS FOR AIRCREW-AIRCRAFT INTERFACES: WHERE SHOULD WE FOCUS OUR EFFORTS?

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1. SUMMARY

This paper identifies and discusses 28 *problem areas* where human factors engineers lack the information needed for development of crewstations for advanced military fighter and attack aircraft. Emphasis of this paper is on naval air missions projected during the early 21st century against land and sea-surface targets. The 28 problem areas are based on the *functions* that the crews must carry out for successful mission accomplishment. *Human capabilities* and *limitations* documented in the human factors literature that relate to these aircrew functions have been used to define the problem areas. The goal is to ensure that aircrew performance will be satisfactory for anticipated air missions.

The 28 problem areas are grouped into nine *human factors problem categories*. For each category, the human factors knowledge and man-machine interface engineering capabilities that should be extended during this decade are noted. The human factors problem categories are (1) physical and physiological stress, (2) vigilance and aircrew alerting, (3) individual differences, (4) information integration, (5) visual displays for various missions, (6) mission management, (7) decision support, (8) automation, and (9) system design and evaluation.

2. BACKGROUND

2.1 Air Warfare in the 21st Century

Constrained and limited-objective warfare has received renewed interest in the past few years, as the dangers of global war have diminished. Both friendly and potentially hostile forces now own numerous kinds of weapons systems that are nearly identical, making positive identification critical prior to air attack. Greater importance is being given to precision targeting and weapon placement that will minimize civilian injuries and collateral damage when responding to aggressor and terrorist threats and attacks.

These new requirements place great burdens on the military aircrews who must make the final decisions about weapon release. Improved crewstations and advanced aircrew-aircraft interfaces of various types have been suggested as solutions to the workload and decision-making problems of military aviators, to minimize errors and to improve reaction time.

Proposed advancements in crewstation display techniques include helmet-mounted displays, three-dimensional voice and other auditory advisories, large flat panel systems, virtual displays, and data fusion for integrated display formats. System control improvements also are proposed: advanced multifunction switches, hands-on-throttle-and-stick controls, voice commands, etc. Intelligent decision aids and expert systems have been offered as answers, along with automation of whatever can be automated.

2.2 Solutions Versus Problems

It is important to note that the crews of advanced aircraft rarely will interact directly with the aircraft and its weapons systems. Instead, they will interact with computers that in turn control the aircraft systems. That is, the crews will serve as *supervisory controllers* of the systems (Ref. 1). Therein lies the promise of improving crew performance for the missions of the 21st century, and also the potential for disaster if the human-computer interfaces are poorly designed.

So far most of the emphasis has been on seeking isolated, piecemeal *solutions* for the advanced aircraft's crews, without first taking a systematic overall look at what the *problems* really are. What human limitations really matter and actually will result in failed missions? What technologies are we proposing as solutions simply because they are feasible—whether or not they address the most important problems? An overview is needed, to put the various proposed solutions into perspective, to consider how proposed advances might fit together or interact, and to aid in setting priorities for the technologies that should be pursued. *Important human factors issues and problems* should be identified, before crewstation designs are solidified.

3. PURPOSE AND APPROACH

The purpose of this study has been to propose a set of human factors engineering issues specifically related to advanced fighter aircraft that should be addressed during this decade. Based on the kinds of naval air missions that can be anticipated early in the 21st century and on standard advanced aircraft systems and components with which aircrews interact, the top-level *functions* that the crew must carry out have been identified. The crew's basic *information* and *control* requirements related to these functions also were identified.

Previously documented human factors books, reports and articles on *human capabilities and limitations* were reviewed. Those capabilities and limitations related to the aircrew's functions and information and control requirements were noted. Based on the resulting lists, potential problem areas that might affect mission accomplishment have been identified.

4. MULTI-ROLE ADVANCED FIGHTER AIRCRAFT

Replacements for many of today's attack and fighter aircraft will be necessary in the next few years, as current systems become unable to meet new requirements. Next-generation tactical aircraft often are referred to as *advanced fighters*, emphasizing the difficult air-to-air combat missions they are expected to carry out. But reduced expenditures for military systems require that most new military aircraft be equipped to serve in several air warfare roles. Air superiority, surveillance, and attack roles all must be considered for new naval tactical aircraft (Fig. 1).

A naval advanced aircraft's *air superiority* fighter function requires that the aircrew be able to engage one or more airborne targets over land or sea, obtain information about the targets necessary for fire control, and direct one or more missiles to intercept the targets. Targets will include adversary bombers and fighters that can be engaged either (1) beyond visual range with long-range or medium-range radar-guided weapons or (2) within visual range using heat-seeking missiles or an aircraft gun. For both situations, it is important that the aircrew have sensors and displayed sensor information designed to meet human perceptual and cognitive needs so the crew will detect the adversary first and launch weapons first.

Beyond-visual-range fighter engagements usually are part of *outer air battle* missions. These engagements require avionics that can assist the aircrew with weapon setup, targeting, and fire control tasks. Although timeliness is not as critical as with some other advanced fighter functions, decision making is especially difficult under beyond-visual-range circumstances, since information usually is uncertain.

Within-visual-range fighter engagements are expected to predominate in most low intensity conflict and constrained and limited-objective warfare scenarios, especially during *strike escort* missions. It should be noted that short-range engagements impose extremely stringent requirements on the aircrew. Careful system design will be required to minimize aircrew response times and the chances of operator errors during the extreme time-related stress of such engagements.

In its *surveillance* role, the advanced fighter aircrew must be able to search for, detect, assess, and use a datalink to report on an attack consisting of one or more air threats (potential targets), during the *outer air battle*. Again, this function may be performed under either beyond-visual-range or within-visual-range conditions, depending on the scenario, rules of engagement, and nature of the threats. In the surveillance role, the aircrew may be required to spend many hours in the air in vigilance tasks: searching for targets and evaluating the combat situation. Aircrew fatigue will be a major problem while carrying out this advanced fighter function.

An *attack* role also must be anticipated for the naval advanced fighter aircraft and its crew, which must be prepared to carry out land or sea *strike* missions when necessary. The U.S. Navy's F/A-18 Hornet aircraft was designed for this dual role from its inception. Several U.S. Navy and Air Force aircraft, originally designed simply as fighters, in recent years have been reconfigured (or reconfiguration plans have been proposed) to handle attacks on surface targets as well. These include the F-14, F-15, and F-16 aircraft. Mission timing and route keeping, task management, and decision making are especially important for the attack role.

5. ADVANCED AIRCRAFT TECHNOLOGIES

The term *advanced fighter technologies* as used here relates to those aircraft systems and capabilities needed so that the aircrew can carry out the advanced fighter missions satisfactorily. At least eight such technologies have significant human factors engineering implications, as identified in Fig. 2 and discussed in the following sections. That is, whether aircrews can reliably carry out the various functions required for each system will be affected by certain basic human capabilities and limitations that have been identified by various researchers.

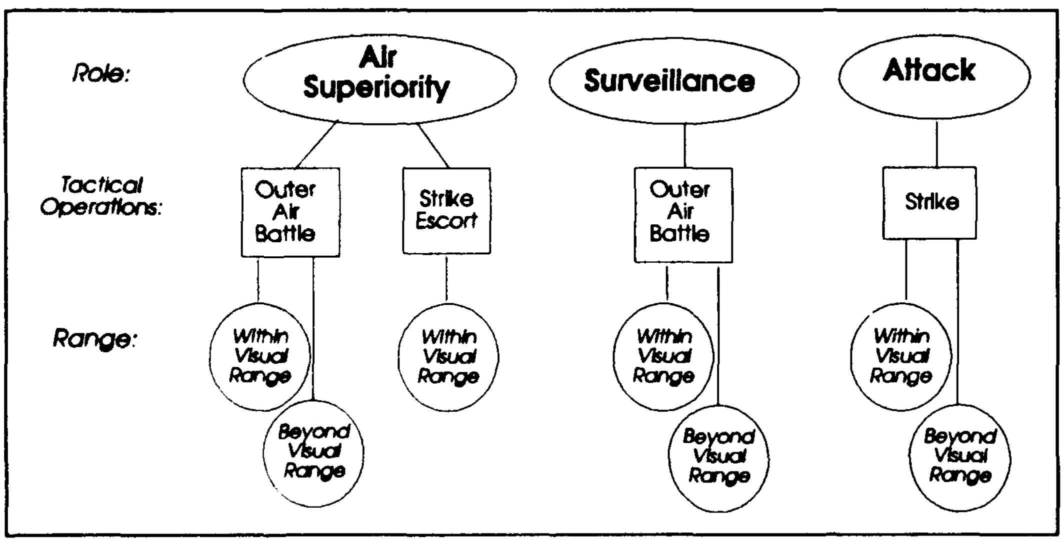

Figure 1. Roles, Tactical Operations, and Areas of Operation for a Naval Advanced Fighter.

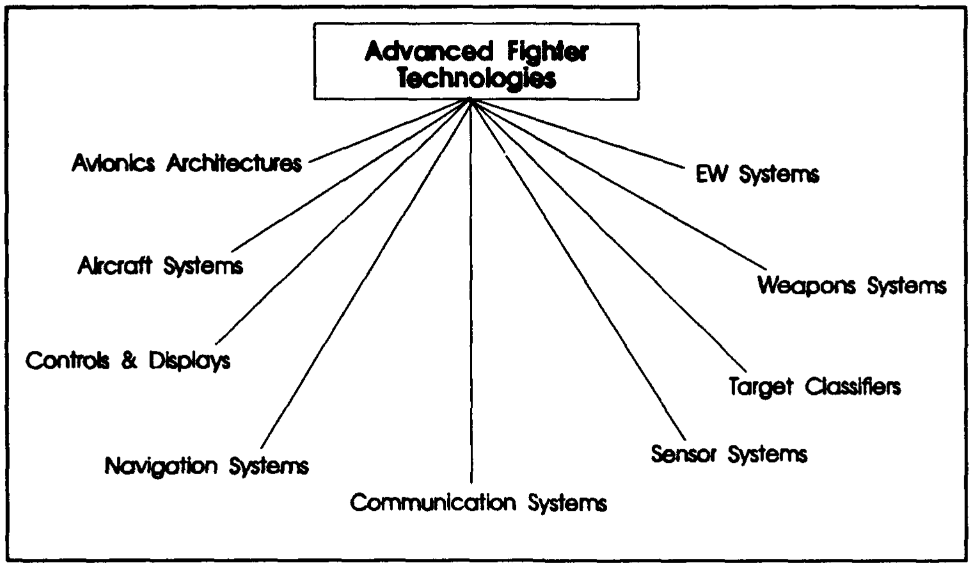

Figure 2. Advanced Fighter Technologies with Significant Human Factors Implications.

What are the functions that the crew of advanced naval aircraft must carry out? A detailed listing of the specific functions related to each of the eight kinds of systems discussed below is beyond the scope of this paper. However, a simple top-level description of crew functions is useful for understanding the kinds of human limitations and capabilities that are important for air missions. Fig. 3 provides an overview of those functions and of the crew's related information and control requirements.

The human capabilities and limitations that are listed for each advanced fighter technology are of course not unique to that specific technology area. Many of the factors actually will influence human performance with several of the advanced fighter systems. However, to avoid redundancy, each factor is listed only once, under the system that may be the most affected by that capability or limitation.

5.1 Avionics and Fire Control System Architecture

For this study, *avionics and fire control system architecture* is defined as the top level hardware and software design that combines the all the subsystems and components that make up the advanced fighter aircraft's avionics and fire control systems. That is, the architecture consists of the interconnections, relationships, and organization of the subsystems that together form an advanced fighter aircraft. Avionics and fire control system architectures should provide top-level integration of all crewstation systems, and also must be compatible with the aircraft, missile systems, and aircrew performance capabilities.

Various studies have noted human capabilities and limitations that may be affected by avionics and fire control system architectures. These capabilities and limitations include the following.

1. *Mental models.* Humans learn and operate systems significantly more efficiently and effectively if they have useful mental models or "pictures" of how the system operates and about the effects their own control actions have (Ref. 2). Thus the overall system architecture should be describable in terms easily comprehended by naval pilots and other crew members (Ref. 3).

2. *Memory limitations and "situational awareness."* Humans generally can retain only five to nine items or "chunks" of data in immediate, short-term memory at one time (Ref. 4). When busy or under stress, humans perform much worse than this; they have difficulty operating on more than a single idea at a time. In essence, they exhibit a form of mental "tunnel vision." Provision should be included to ensure that the aircrews know what mission tasks have been completed, and will remember and perform all remaining required tasks, even under the most difficult circumstances. This includes resuming system control following recovery from g-induced loss of consciousness (GLOC).

3. *Decision-making.* In the *beyond-visual-range fighter* role, the aircrew must evaluate uncertain information provided by the data fusion system, then determine whether to engage long-range targets. Decision-making assistance will be needed as part of system architecture to optimize the crew's performance of this task (Ref. 5).

4. *Time stress.* In the *within-visual-range fighter* role, the aircrew must process information, make correct decisions, and complete appropriate responses with extreme rapidity. Pilots restrict their "sampling" of information to what they perceive as "most important"—and are not always right (Ref. 2). System architecture should include intuitive information display and adaptive automation (Ref. 6) of some control functions for this fighter role.

1. **Aircrew function:** *Premission and midmission planning.*
   Required information: Mission plans and status.
   Required controls: Mission planning and plan modification controls.
2. **Aircrew function:** *Understand system components and component integration.*
   Required information: Online documentation about aircraft systems, mission, and tactics.
   Required controls: Controls to request system architecture and status information.
3. **Aircrew function:** *Understand integrated information and integration systems.*
   Required information: Integrated data from all compatible sources.
   Required controls: Information output display optimization controls.
4. **Aircrew function:** *Top-level system control.*
   Required information: (a) Status of supervisory control of all systems. (b) Top-level status of all systems.
   Required controls: Top-level moding controls.
5. **Aircrew function:** *Monitor and interpret aircraft status information and make decisions.*
   Required information: Aircraft attitude, altitude, speed, energy and power, force due to gravity, location, direction of flight, fuel status.
   Required controls: Information output optimization controls.
6. **Aircrew function:** *Control the aircraft.*
   Required information: Current and projected status of aircraft systems.
   Required controls: Controls for attitude, altitude, airspeed, direction of flight.
7. **Aircrew function:** *Monitor and interpret onboard system status and mission status information and make decisions.*
   Required information: Control and display requirements, setup, mode, and status information.
   Required controls: Information output optimization controls.
8. **Aircrew function:** *Manage onboard systems.*
   Required information: Requirements, settings, modes, and status of all systems.
   Required controls: System setting and mode optimization controls.
9. **Aircrew function:** *Monitor and interpret system-provided information and make decisions.*
   Required information: (a) Current setup, mode, and status information for all systems. (b) Mission and tactics information related to each system. (c) Data. provided by each onboard system.
   Required controls: System output optimization controls.
10. **Aircrew function:** *Recognize and overcome system problems.*
    Required information: Warnings about system problems.
    Required controls: Controls for recovery from system problems.

Figure 3. Top-Level Listing of Aircrew Functions and Information and Control Requirements.

5. *Vigilance and fatigue.* In its *surveillance* role, the aircrew will be required to spend many hours seeking and evaluating potential targets. System moding and display formats should be optimized to yield satisfactory target acquisition performance. System architectures should support the pilot's needs for stimulation and interesting tasks, critical for maintenance of a vigilant state (Ref. 7).

6. *Task management.* In the *attack* role, target acquisition and precise completion of tactical maneuvers requires system architecture that includes intelligent decision support (Ref. 5) and adaptive automation (Ref. 6) of some control functions.

Several more general considerations also should be considered during development of avionics system architectures for advanced fighters. These considerations include the following.

1. *Systems approach.* From the aircrew's perspective, all components of an advanced fighter are part of a single system: the aircraft. For satisfactory crew performance, the aircraft and all its subsystems must incorporate a single, consistent control and display philosophy (Ref. 8). That is, display formats, abbreviations and acronyms, symbol meanings, information display techniques, control assignments and operations, procedures, and relative degrees of automation should be consistent throughout (Ref. 6).

2. *Layered interface.* Over time, aircrews with various levels of sophistication will use the advanced fighter system. The architecture should provide novice users with a menu-driven interface, but permit experienced users to circumvent the menus and give direct commands to the system for rapid operation (Ref. 9). "Deep windowing" is bad; people get lost when they must navigate through numerous menu levels.

3. *Separation of user interface code.* The architecture should be designed to separate the programs and code that determine specific display and control operations (the user interface) from the programs that actually operate the systems. This is important to facilitate rapid and inexpensive improvements in the user interface, as aircrew personnel evaluate the system and propose changes (Ref. 10).

4. *Logical command and option ordering.* Commands and options should form logical and consistent sets. The command functions and the names given to commands should be predictable by the aircrew operators (Ref. 8).

5. *Minimal aircrew operations.* System control actions carried out the by the aircrew must be simple, logical, and consistent, yet flexible enough that the aircrew may tailor the order in which actions are completed both to the mission and for personal preferences.

6. *No "garden pathing."* Under no circumstances should the architecture allow the aircrew to continue data entry or other system operations after an entry has resulted in an error condition that will nullify the entire procedure. Error checking should be continuous. The aircrew should be

notified immediately if a disallowed action has been taken, for immediate correction without loss of other operator inputs (Ref. 9).

7. *One-time data entry.* Under no circumstances should the aircrew be required to enter the same data more than once. All systems requiring data should be able to access a single source and obtain whatever is needed from a single (usually premission) aircrew-entered data file (Ref. 8).

8. *System response time.* Aircrew commands, menu selections, and data entry actions must be acknowledged rapidly; delays should not exceed 0.2 second (Ref. 11). If the aircrew must make a real-time response, the systems must provide a satisfactory answer in the available time, with solution quality improving monotonically with time (Ref. 12).

9. *Aircrew trust.* The advanced fighter system architecture should ensure that all aircrew-delegated, mission-critical functions are performed reliably by the systems to which they are delegated (Ref. 9). The systems should recommend intelligent options, and exercise the level of autonomy conferred by the aircrew. The aircrew remains the ultimate source of mission priorities and a vital source of status and situation information.

5.2 Aircraft Systems

For this study, *aircraft systems* are defined as those used by the aircrew for monitoring and controlling aircraft flight. These systems include the mission and aircraft computers; engines; aircraft control surfaces; fuel systems; and monitoring systems related to attitude, altitude, airspeed, and direction of flight. Aircraft systems should provide the required airspeeds, fuel capacities, and other performance and operational capabilities needed for various operational roles, yet be compatible with avionics and fire control systems, with missile system payloads, and with aircrew capabilities.

Human capabilities and limitations related to aircraft system functions are discussed below.

1. *Spatial disorientation and vertigo.* Various flight conditions, including the use of night vision goggles (NVGs) can result in the aircrew becoming disoriented regarding their position or orientation with respect to the earth (Ref. 13, 14). Virtually all pilots experience this at some time (Ref. 15). Aircraft systems should be designed to minimize procedures that result in disorientation, to aid in recovery from unusual attitudes, and to provide ground proximity warnings.

2. *Continuous control.* Continuous closed-loop control tasks required for aircraft flight control and navigation are extremely demanding for the aircrew (Ref. 16). These tasks form a workload baseline on which other, noncontinuous aircrew tasks build. Thus workload minimization should begin with making basic flight control procedures as simple and intuitive as possible. Careful automation and the use of artificial intelligence techniques should be considered.

3. *G-induced loss of consciousness.* Increasing aircraft speed, acceleration, and turning abilities beyond those tolerated by humans is definitely counterproductive. Crewstation design should minimize the probability that the aircrew will suffer degraded visual acuity, reduced ability to do mental processing, and GLOC (Ref. 17). When conditions warrant, the ability should be provided for the aircrew to turn some critical functions and procedures over to automated systems. In some situations, the ability of aircraft systems to sense that the crew has been incapacitated will be necessary so that automatic control can be initiated.

4. *Eye damage.* The human visual system is extremely delicate and subject to temporary or permanent damage from brilliant flashes and from lasers. Some instantaneous procedure (such as making the helmet visor or canopy opaque) should be provided to protect aircrew eyes from such dangers.

5.3 Control and Display Systems

For this study, *control* and *display systems* in the crewstation are those devices used by the aircrew (1) to give commands to the aircraft and its systems (usually indirectly, through a computer system), and (2) to obtain information from the aircraft and its systems (again, usually with a computer system serving as intermediary). Crewstation control and display systems should enable the aircrew to perform control actions and to obtain information as needed to manage the aircraft and weapons systems. Task assistance systems are needed, including various aircrew-selected levels of automation as appropriate for the operational situation. Decision-aiding systems also are required, possibly including expert systems.

Aircraft *control systems* include the traditional throttle and control stick, plus a selection of pushbuttons, toggle switches, and joysticks located on the throttle and stick (the "hands-on-throttle-and-stick" or HOTAS control philosophy). Some control operations are provided via dedicated switches (e.g., weapon jettison and "Master Arm" selections). However, as aircrew functions have proliferated, multipurpose controls are used where practical to minimize crewstation crowding and clutter. Multipurpose pushbuttons often are integral to multifunction displays, so that part of the display surface can be used to label the switches with their current functions. Other multipurpose pushbuttons are part of control systems that include a 10-digit keypad for entry of latitude/longitude, range, and other numeric data.

Aircraft *display systems* rely increasingly on presenting critical information "head up" so the aircrew does not have to look down into the cockpit and search for needed data. The head-up display (HUD) currently is the primary device in this category, providing flight, navigation, and targeting data when the pilot is looking forward through his windscreen. However, advanced fighter display concepts also should include helmet-mounted displays (HMDs) that can provide similar data wherever the pilot is looking (Ref. 18). Since clutter and the danger of distractions prevent

displaying more than the minimum critical information head up, "head down" multifunction displays also are needed to provide detailed information about aircraft, weapon, target, and threat status. Crewstation research also includes concepts such as the "big picture" cockpit where a single flat panel or high-resolution TV display fills the main instrument panel and replaces all the individual display devices with integrated presentation of information as it is required (Ref. 19). "Virtual cockpits" generated using HMDs or hologram technology to present "controls and displays in the air" also are being explored (Ref. 20).

Consideration of various modern crewstation control and display concepts for advanced fighter applications is important. However, the ability of the aircrew to perform all mission-required tasks using many of these advanced concepts is largely untested at present.

Human capabilities and limitations related to the operation and use of controls and displays are discussed below.

1. *Individual differences.* Humans vary widely in their cognitive, physiological, and physical requirements related to the use of control and display systems. As a result, several factors will strongly affect aircrew ability to carry out the advanced fighter missions satisfactorily. These include the individual's (a) prior training and aircraft-related experiences, (b) peripheral vision field size, (c) auditory decrement at some frequencies due to noise exposure, (d) ease of distraction, (e) ability to maintain a vigilant state, (f) reaction to stress, (g) cerebral hemisphere preference (whether he demonstrates primarily a spatial or verbal orientation), (h) locus of control (internal or external motivation), (i) risk aversiveness level, (j) willingness to yield control to his systems, (k) decision response time, and (l) control reaction time (Ref. 15). In the past, crewstation designers have ignored individual differences. Controls and displays have been optimized for the "average" or "median" aircrew. It now is possible to design aircraft displays and controls so that each crewmember can tailor to his personal needs what he sees and hears and how he controls his systems. For optimum aircrew performance of the advanced fighter mission, this approach definitely should be considered for advanced fighter development.

2. *Empty field myopia and accommodation-convergence micropsia.* When looking at HUD and HMD symbols against the sky, for some people the eye tends to focus at about 2 feet out (even though HUDs and HMDs supposedly are focused at infinity). This results in misjudgments of the sizes of and distances to external objects (such as other aircraft), when these come into view (Ref. 21). These problems are aggravated by the use of NVGs. Aircraft systems should be designed to minimize visual illusions.

3. *Head-up missions.* Even with modern sensors, the fighter role requires that the aircrew be able to focus attention "out the window" during the heat of battle. The importance of head-up displays and controls to satisfactory mission accomplishment cannot be overemphasized. Thus during design of the advanced fighter crewstation major attention should be paid to optimum integration of head-up and helmet-mounted displays, NVGs, and auditory cueing, along with that data which still must be presented head down. Control systems should rely strongly on voice commands (Ref. 22) and on head- and eye-tracking devices; requirements to use manual controls should be minimized.

4. *Environmental protection gear.* Aircrews operate aircraft controls and view displays while tightly strapped into an ejection seat and wearing restrictive clothing and gloves. More recently, the crew also must be able to obtain system information and to control all of their systems while protected by cumbersome chemical and biological warfare gear. All required aircrew personal gear should be predefined and considered during development of the crewstation, for satisfactory advanced fighter mission accomplishment.

5.4 Navigation Systems

For this study, *navigation systems* are defined as equipment used by the aircrew to monitor and control aircraft position and direction of flight. These systems include inertial navigation systems, compasses, digitized maps, and signals from global positioning satellites. They also include computer systems that store data related to the mission plan, flight path, event timing, and tactics. Navigation systems must be capable of navigating to any point by way of a predetermined course, must provide position (latitude and longitude) and velocity vector information continuously, and must support cooperative engagements.

Human capabilities and limitations related to navigation system functions are discussed below.

1. *Ability to replan.* When unexpected events result in unforeseen situations, humans generally are very good at reprioritizing and replanning to accommodate to the situation. However, humans are *not* good at mental calculations or holding more than five to nine items in mind at one time. Thus, the ability to replan a mission in the air if required should be augmented by computer aids that can assist with the required replanning tasks.

2. *Decision making.* Humans primarily reason from examples, based on what has worked for them before and what they can recall easily. They rarely can consider more than three or four hypotheses at one time. They refuse to give up a theory or model unless they have another with which to replace it. They also reason using backward chaining, choosing a goal or solution then seeking a way to reach that goal (Ref. 23). Thus, when navigation to or from the target area requires that the aircrew make decisions, computer assistance should be provided (a) to propose the most reasonable alternatives and hypotheses, (b) to help the aircrew visualize these alternatives and objectively weigh their pros and cons, and (c) to provide the sequence of steps necessary to reach the solution or desired goal (Ref. 24).

5.5 Communications Systems
For this study, *communications systems* are defined as those onboard systems used by the aircrew to communicate between themselves and with surface, subsurface, ground-based, and other airborne elements, including both manned stations and automatic datalink facilities. *Communications systems* must transmit and receive jam-free data continuously to and from any of the force structure elements employed in the specific tactical operations, including voice, datalink, and missile command guidance communications.

Human capabilities and limitations related to communications and communication systems are discussed below.

1. *Information fusion.* During the mission, the aircrew must utilize real-time voice and datalinked information in conjunction with intelligence, geographic, and cultural data entered into the system during premission planning. Humans have a tendency to give the greatest weight to earlier data, using recent data primarily to seek confirmation for that early data rather than to test it (Ref. 23). Techniques are needed to integrate data from real-time communications systems with premission data, to provide the aircrew with the best possible objective, unbiased "world picture" as that picture changes dynamically.

2. *Information uncertainty.* Humans have a tendency to treat all information as if it were equally reliable. They generally are not good at estimating probabilities, or at weighing and comparing the relative "goodness" of data from various sources. They are especially bad at combining probabilities and at including *a priori* probabilities in their mental calculations (Ref. 23). The advanced fighter systems should provide the aircrew with assistance in evaluating the level of certainty for information communicated from various individual sources, plus the level of certainty for integrated information from several sources.

5.6 Sensor Systems
For this study, *sensor systems* are defined as those onboard avionics systems that provide real-time data to the aircrew about targets and some kinds of threats. Sensors include both passive and active systems. They may be based on radar, television, infrared, radio and millimeter wave, and other technologies. Sensor systems must be sensitive enough to provide the characteristics of anticipated targets in various operational electromagnetic and climatic environments.

Human capabilities and limitations related to the use of sensor systems are discussed below.

1. *Monitoring and vigilance.* The human generally is easily distracted and is a very poor system monitor (Ref 15). For satisfactory mission performance, some level of automation probably will be needed for monitoring sensor output for prespecified events that occur infrequently and unexpectedly, so that the aircrew can be alerted.

2. *Mental processing of information.* A great deal of research has been done on the best ways to display both sensor images and computer-generated formats based on sensor outputs, for satisfactory aircrew understanding and performance. Appropriate handbooks, sets of guidelines, and related materials should be used in design of the advanced fighter sensor output displays to ensure that symbols and formats are used which have been tested and evaluated (Ref. 8).

3. *Operational decision making.* If sensor image quality is uncertain, the aircrew will have a hard time deciding whether to trust what is displayed. Providing an associated image quality metric that indicates the current relative "goodness" of sensor output will result in better targeting decisions.

5.7. Targeting Systems
For this study, *targeting systems* are defined as those onboard sensor and computer systems that assist the aircrew in detecting, identifying (friendly, unknown, hostile), classifying (specific target type), and designating airborne, surface, and ground targets. The classification abilities of onboard targeting systems may be enhanced by computer-based premission data related to anticipated targets and various characteristics of these targets, and by up-to-date datalinked information from other airborne platforms and from surface assets. It should be noted that basic target aircrew functions related to targeting system control and information interpretation are similar to those required for the use of aircraft *sensor systems* in general. Target detection and classification systems must detect, identify, and classify targets at maximum surveillance and engagement acquisition ranges.

Human capabilities and limitations related to targeting systems are discussed below.

1. *Information gathering.* During decision making, humans tend to seek far more information than they can easily absorb, especially if decisions are hard or outcomes expensive (as is the case during target classification) (Ref. 25). As information is gathered, humans become more confident in their decisions, but not necessarily more correct in their decisions (Ref. 23).

2. *Anchored judgments.* While considering alternatives, undue weighting is given to early evidence, which anchors the judgment at a starting value (Ref. 26). Then humans tend to seek (and usually find) additional information that confirms the decision or chosen course of action, rather than to test it; they exhibit "cognitive tunnel vision" (Ref. 25). This is especially true under conditions of high stress and workload such as when deciding whether an object is to be attacked. Humans will not abandon a hypothesis or theory (no matter how bad) unless they have another with which to replace it (Ref. 23).

3. *Limited consideration of sources and alternatives.* Limitations of human attention and working memory make it impossible to integrate information simultaneously from more than a few sources (Ref. 25). This limitation can affect

whether an adversary is identified in time for first launch of an air-to-air missile. In addition, during decision making humans tend to focus on a few critical attributes at a time, and consider only the two to four alternatives or options that rank highest on those particular attributes (Ref. 23).

4. *Conservative judgments.* Humans generally are "risk aversive" and exhibit a central tendency of odds; extreme values are not given as much confidence as might be optimum for reliably determining the nature of a possible target (Ref. 25).

5.8. Weapons Interface and Control Systems

For this study, *weapons interface and control* systems are defined as those onboard systems used for weapon carriage, to initialize and prepare weapons for release, and to control inflight weapons. Computer systems required for specific weapons also are included in this definition. Weapons interface and control systems must be capable of carrying all required weapons and of programming and controlling those weapons during carriage and in flight.

Human capabilities and limitations related to weapons interface and control systems are discussed below.

1. *Top-level weapon moding.* Humans are especially error prone when required to complete a number of detailed procedures under time stress (Ref. 27). To minimize this effect, the weapons systems should self-initialize to near-optimum states for a given mission and mission phase. For example, one-switch selection of "air-to-air mode" should configure the stores management systems for air combat.

2. *Adaptive automation.* Weapon delivery is workload intensive, and automation of some functions will be necessary. Automation levels can be adapted to the mission and situation in three ways: (a) through fixed automation levels, predetermined by the aircraft development team, that are considered appropriate for a given mission phase, task, and situation; (b) via aircrew selection and tailoring of task automation levels prior to each mission, to suit personal styles (Ref. 28); and (c) through the use of expert systems or neural network systems that determine the aircrew's "intent" based on the current situation, and select appropriate automation levels (Ref. 29). The proper use and mix of these techniques will be important for aircrew performance.

3. *Remote vehicle control.* Aircrew datalink control of an inflight missile is similar to control of any remotely-piloted vehicle. Design of such systems so that human performance will be satisfactory is not easy, especially for the terminal phase of weapon delivery. Existing guidelines should be heeded (Ref. 11).

5.9. Electronic Warfare Systems

For this study, *electronic warfare (EW) systems* are defined as those onboard systems related to electromagnetic (radio frequency and electro-optic) signal exploitation and electronic warfare technologies. These include electronic surveillance devices; radar warning receivers; signal repeaters and jammers; expendable countermeasures stores such as chaff, flares, and minijammers; and missile detection systems. It should be noted that basic aircrew functions related to EW system control and information interpretation are similar to those required for the use of aircraft *sensor systems* in general. EW systems must detect, analyze, and assess all electromagnetic signals to determine bearing, category, and number of emitters; provide automatic and/or manual control for management of offensive and defensive EW capabilities; and support targeting and missile system fire control functions.

Human capabilities and limitations related to EW systems are discussed below.

1. *Information interpretation.* In high-stress situations such as the presence of missile threats (and especially when a missile-in-the-air alert has been received), human mental functioning is undependable. Displayed information should rely on simple, intuitive diagrams, rather than words or other information presentation modes that require interpretation. Information should be provided in the form of *commands*—directing the crew precisely what to do, and when to do it (Ref. 15).

2. *Memory fallibility.* Short-term or working memory is seriously hampered by stress. The ability of the aircrew to recall required procedures cannot be depended on. Cues should be provided to help the crew recognize necessary sequential actions.

3. *Visual system overload.* The aircrew must keep track of a great deal of information needed for satisfactory situation assessment while trying to complete a mission under high-threat conditions. Most of this information usually is received visually. Humans are capable of processing more information if it is received using several sensory systems (e.g., both visual and auditory signals) and if the modality of the signal is compatible with normal mental processing of the particular type of information (e.g., spatial or verbal) (Ref. 25). Ways to reduce visual overload should be sought, with consideration of substituting auditory signals to represent appropriate kinds of information.

4. *Control of self-protect equipment.* To reduce workload and the necessity of making decisions, aircrews should have the option of commanding automatic signal jamming and/or the dispensing of countermeasures when appropriate. They also must be able to countermand such automation and assume manual control as desired. As with the visual

system, the aircrew's manual control abilities are near their limits. Techniques are needed to permit system control using other modalities, including voice commands and commands given via head or eye movements.

6. HUMAN FACTORS PROBLEM AREAS

While a list of aviation-related human capabilities and limitations is interesting, it is not especially useful in laying out needed research programs related to aircrew-aircraft interfaces. Where precisely should we focus our efforts? To answer this question, the 40-odd items listed above have been reviewed, organized, and consolidated into 28 *problem areas* related to human factors engineering. These are areas where human factors engineers currently lack some of the information essential for development of crewstations for advanced military fighter and attack aircraft. What is needed (at least in part) to solve each of the problems also has been identified and is documented below.

The 28 human factors issues can be separated into nine categories, as shown in Fig. 4. Several of these categories were included in the FY-1991 *U.S. Department of Defense Critical Technologies Plan* (Ref. 30). The DoD's report documents 20 technologies considered to be the most important to ensuring the long-term qualitative superiority of United States weapons systems. These critical technologies include (1) machine intelligence and robotics, (2) simulation and modeling, (3) signal processing, and (4) data fusion.

6.1 Physical and Physiological Stress.

1. **Problem:** *Environmental protection gear.* **Needed:** Gear that protects from biological and chemical agents without interfering with aircrew tasks.

2. **Problem:** *G-induced loss of consciousness.* **Needed:** (a) Techniques for automatically determining when GLOC is impending. (b) Techniques for displaying "GLOC impending" warning to a dazed aviator. (c) Automatic aircraft control during GLOC episodes. (d) Techniques for informing the crew of system status and returning control when consciousness is regained.

3. **Problem:** *Laser and flash protection.* **Needed:** Techniques for providing eye protection that do not interfere with mission tasks.

6.2 Vigilance and Aircrew Alerting

4. **Problem:** *"Situational awareness."* **Needed:** Research to demonstrate techniques and procedures that result in satisfactory awareness and assessment of aircraft and mission status.

5. **Problem:** *Vigilance.* **Needed:** (a) Techniques for monitoring vigilance and alerting the crew when vigilance drops. (b) Techniques for directing the aircrew to take specific emergency actions. (c) Techniques for automating critical monitoring tasks without reducing aircrew vigilance levels. (d) Techniques for maintaining vigilance levels on long missions.

6. **Problem:** *Recovery from unusual attitudes.* **Needed:** Research on sensory modalities and display techniques for alerting the pilot and advising how to return to a safe flight envelope.

7. **Problem:** *Ground proximity warnings.* **Needed:** Techniques for immediate, intuitive display of aircraft data that will minimize chances of flight into terrain.

8. **Problem:** *First detection and launch.* **Needed:** Equipment and procedures for acquiring air adversaries at maximum range and alerting the crew for effective weapon launch.

6.3 Individual Differences

9. **Problem:** *Sensory perception.* **Needed:** (a) Research on performance differences with various information presentation modalities and formats, as a function of the individual and situation. (b) Techniques for aircrew tailoring

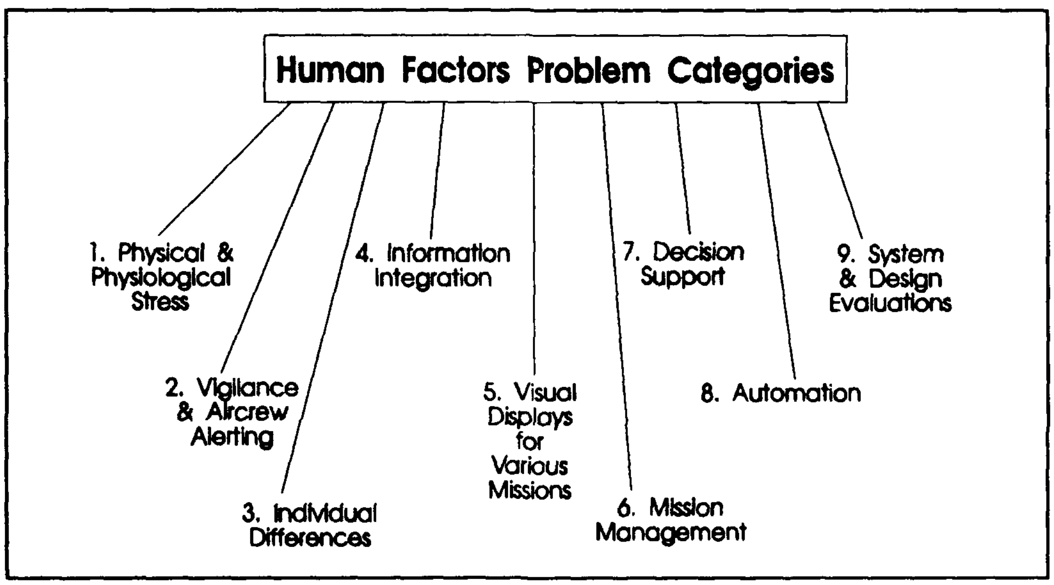

Figure 4. Categories of Problems for Advanced Fighter Aircrews Related to Human Factors.

of display modalities and formats (both premission and midmission), as needs and conditions vary.

10. **Problem:** *Mental processing.* **Needed:** Techniques to ensure that crewstation equipment and mission procedures are consistent with aircrew expectations and mental models.

11. **Problem:** *Response and control.* **Needed:** Techniques for aircrew tailoring of controls and operating procedures (both premission and midmission), as needs and conditions vary.

6.4 Information Integration

12. **Problem:** *Integrated information databases.* **Needed:** (a) Techniques to permit viewing of either integrated, single-source, or multi-source (crew-selected) data, as desired. (b) Procedures and guidelines for weighting data according to uncertainty levels prior to integration. (c) Techniques that advise the aircrew of the sources of data and that permit the crew to evaluate the "goodness" of both integrated and unintegrated data. (d) Techniques that result in common, consistent symbols and formats that are intuitively understandable, regardless of the information source or sources.

13. **Problem:** *Auditory integrated information displays.* **Needed:** Research on the best uses for auditory displays, best types of auditory signals for various purposes, and most effective vocal frequencies, words, and phrases for verbal displays, under all mission conditions.

14. **Problem:** *Visual integrated information displays.* **Needed:** Procedures and guidelines for design of visual formats presented on various display surfaces (HUDs, HMDs, etc.), for satisfactory perception and understanding of and responses to integrated data under all mission conditions.

15. **Problem:** *Display of uncertain information.* **Needed:** Techniques for displaying uncertain information for intuitive understanding by the aircrew.

6.5 Visual Displays for Various Missions

16. **Problem:** *Air superiority missions.* **Needed:** (a) Research on HUD and HMD information display to minimize vertigo and disorientation, and to counteract target distance and size illusions. (b) Research on HMD formats that can be used effectively during air combat missions.

17. **Problem:** *Surveillance and attack missions.* **Needed:** (a) Techniques for effectively partitioning and integrating head-up and head-down information. (b) Techniques for effective display of target location, offset aimpoint, and weapon release-point information. (c) Research on minimizing vertigo, disorientation, and illusions when NVGs are used. (d) Techniques for display of information on NVGs so it is cognitively compatible with other displayed information.

6.6 Mission Management

18. **Problem:** *Mission status.* **Needed:** (a) Techniques to provide meaningful combinations of target area, target, and weapon information. (b) Techniques to provide tactics-related information and requirements developed during mission planning. (c) Techniques to remind the crew of preplanned task sequences and timing, status with respect to the plans, and uncompleted critical tasks. (d) Techniques for displaying planned versus actual aircraft and mission data and status. (e) Equipment and techniques for quick and easy partial or total replanning of the mission during the mission.

19. **Problem:** *System status.* **Needed:** Techniques to inform the crew of available system modes, current system status, and system interrelationships, and to alert the crew to system problems.

20. **Problem:** *System control.* **Needed:** (a) Alternate techniques for system control, including voice commands, body positioning, head or eye movements, and brain activity, and determination of the kinds of tasks for which each technique is satisfactory. (b) Research on the maximum quantity and optimum kinds of controls for HOTAS operations. (c) Techniques for simple control of sensor setup parameters for optimum imagery. (d) Techniques and procedures for simple designation and undesignation of air and surface targets. (e) Techniques for optimum display of datalinked information from inflight weapons, and optimum techniques for controlling weapons in flight.

6.7 Decision Support

21. **Problem:** *Decision support techniques.* **Needed:** (a) Research to determine and prioritize the aircrew tasks for which aiding is needed, and the conditions under which aids will be used. (b) Research on the best decision support technique for each kind of task. (c) Research on the best aiding medium and aid development technique for each kind of aid. (d) Research on the most appropriate user interface for each decision support system. (e) Techniques to help operators integrate information from a variety of sources, overcome typical human cognitive biases, and consider and weigh all reasonable alternatives when making decisions.

22. **Problem:** *Decision aid usefulness.* **Needed:** Techniques to ensure that aids can be trusted, can operate in real time, and can justify their options and selections for the aircrew.

6.8 Automation

23. **Problem:** *What to automate.* **Needed:** (a) Procedures and guidelines that define tedious or difficult advanced fighter tasks that are suitable for automation. (b) Procedures and guidelines to determine the optimum automation level and technique for each candidate task.

24. **Problem:** *Adaptive automation.* **Needed:** (a) Research to determine the optimum kind and level of adaptive automation for various purposes. (b) Research to develop adaptive automation technologies. (c) Research to develop aircrew procedures for use of adaptive automation systems. (d) Research to determine appropriate display formats and

control configurations for use with adaptive automation systems.

25. **Problem:** *Overriding automation.* **Needed:** Techniques for overriding automated systems intuitively and rapidly in emergencies.

6.9 System Design and Evaluations

26. **Problem:** *Specifications and statements of work.* **Needed:** Procedures and guidelines to ensure that advanced fighter specifications and statements of work require contractor estimates, demonstrations, and evaluations of satisfactory aircrew performance early enough to affect designs.

27. **Problem:** *How to test.* **Needed:** (a) Procedures and guidelines for optimum allocation of mission functions among aircrew personnel and between the aircrew and aircraft systems. (b) Procedures and guidelines to determine that crewstation equipment is optimum for the missions. (c) Procedures and guidelines to determine that crewstation equipment layout is optimum for the missions. (d) Procedures and guidelines to ensure that required aircrew operations and tasks can be completed in accordance with mission requirements.

28. **Problem:** *How to evaluate.* **Needed:** (a) Procedures, techniques, and tools to specify what will be satisfactory levels of aircrew performance. (b) Procedures, techniques, and tools to evaluate whether the contractor's designs will meet specified levels of aircrew performance.

7. CONCLUSIONS AND RECOMMENDATIONS

The 28 human factors problem areas discussed above may provide a near-term basis for setting some of our human factors research and development priorities related to the aircrew-aircraft interface. It should be noted that these problems are *not* listed in priority order. Although each type of problem is critical to the aircrew in some manner, further analysis is needed to determine (1) how relatively important this problem area is to mission success, (2) the extent of work needed to address each problem, and (3) the order in which the problem areas should be addressed for greatest efficiency and effectiveness.

The picture is not entirely gloomy. A great deal already is widely known and well understood about how to optimize human performance under various conditions. Some of that information has been included in this paper, as it applies specifically to design of aircrew-aircraft interfaces for advanced fighters. Much more is documented in widely available books, reports, and articles.

The above-noted 28 problem areas probably cannot all be satisfactorily addressed in this decade. However, thoughtful collection of new information and appropriate use of existing human factors knowledge will significantly increase the chances that advanced aircrew-aircraft interfaces will be satisfactory and that aircrews will be able to carry out constrained and limited objective naval air missions needed in the early 21st century.

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Discussion

Paper 3

DISCUSSION

QUESTION R.LITTLE

How do you specify the requirements in engineering terms?

REPLY

This is a very difficult problem!

Advanced Cockpit - Mission and Image Management

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1. INTRODUCTION

Modern cockpit designs require new modular architectures for MISSION and IMAGE-MANAGEMENT with regards to hardware and software aspects.
The main task (see figure: 1) is the collection of aircraft specific data using the appropriate DATA MANAGEMENT, the transformation of such data to graphical images with the appropriate LOGICAL IMAGE MANAGEMENT, the generation of physical graphical images on several image devices by PHYSICAL IMAGE MANAGEMENT and the conversion and combination/mixing of physical graphical data with the data, created by external video sensors using VIDEO MANAGEMENT. Finally the video-data has to be presented on several devices, like HEAD DOWN-, HEAD UP and HELMET MOUNTED DISPLAYS.

The main goal for us as basic system supplier is to give the application programmer an abstract high-level interface for all these functions. This is to be done and is specially supported by the program language Ada, which is the required language for military and civil aircraft applications.

The system described herein was developed for the german experimental helicopter program AVT and two special applications for the X31A experimental aircraft.

2. SYSTEM ARCHITECTURE

The system architecture (see figure: 2) consists of several modules connected to a system bus, which actually is the VMEbus. For future aspects this could also be the PIbus or the SAFEbus, or a high speed serial data busses which not has been defined. The system bus ensure the intermodule communication and must support multiprocessing as well as direct memory access (DMA) and fast interrupt capability.

The basic architecture connects all modules via a global system bus. These modules are data interfaces, central processing units, memory modules, graphic processing modules and video mixing and video conversion modules.

In complex systems with just one system bus, this one bus could be the bottle neck. Because of this a complex system may require more than just one system bus. To overcome this problem we've designed several bus structures.

2.1. Single Bus architecture

When the data transfer rate and the interrupt load of the system are below a specific value, a single bus structure, where all modules are connected to one bus, will be sufficient (see figure: 3).

2.2. Separate Bus architecture

In this solution, some modules can be connected to an additional bus to shift the data-transfer load from the system bus to this additional bus. We are using the VSBbus in addition to the VMEbus. That VSBbus is connected parallel to the VMEbus over the same P1/P2 connector (see figure: 4).

A good solution could be in connecting CPUs to special data or graphic processing devices, which require a more complex device handling and interaction.

2.3. Splitted Bus

This solution cuts the global system bus in halves, connected via a DPR memory interface. This memory can be handled from both sides under the same address and supports the interprocessor communication with read-modify-write capability. Two CPUs communicating on one bus side, do this in the same way as on both sides over the DPR memory interface. They don't recognize the difference. The system can grow up to the double bus load with the same communication facility (see figure: 5).

2.4. Mixed-Bus architecture

The mixed bus structure is a mixture of the SEPARATE and the SPLITTED bus structure and combines their advantages.

3. SYSTEM COMPONENTS

3.1. Interfaces

The main goal here is to collect all the data from different links and make it available to the system. This has to be done by local device intelligence to minimize the handling overhead for the system (see figure: 6). Because of the history of aircraft manufacturing, many different data links exist.

For future aspects the collection of data of different links and the transformation to one modem link (e. ARINC-629) could be implemented in separate cabinets.

3.1.1. Serial interfaces

Serial links, such as RS232, RS422, synchronous or asynchronous are to be handled with local device intelligence to form single data items into complete data sets and make them available to the system. Because the devices generate an interrupt for each single data item, a local CPU is required to decrease the interrupt load on the global system bus.

3.1.2. Parallel

The main goal here is to start and stop processes connected to single inputs and produce single outputs. This has to be done by interrupt generation on input value changes, asynchronous reads and simple writes.

3.1.3. Mil-1553 interfaces

When operating as a bus-controller a local intelligence, which supports several synchronous data frames with predefined error handling is required. For the system a synchronous and an asynchronous data interface are required. The asynchronous data interface and the error exceptions have to be implemented via interrupts to support short latency and determinisms.

When operating as a remote-terminal the device handling is more simple and will be covered by the devices available on the market. Local intelligence is only required when special synchronous data handling is required.

3.1.4. Arinc-429 interfaces

Synchronous reads are supported by interrupts and asynchronous reads are supported by a memory driven interface. Writing data are supported by special FIFO-buffers, where the data can be filled in at the maximum bus-speed by the system.

3.1.5. Arinc-629 interfaces

Synchronous reads are supported by interrupts and asynchronous reads are supported by a memory driven interface. Writing data is supported with special page-buffers, where the data can be filled with bus-speed by the system. The data transfer, the protocol and the framing are supported directly by the hardware.

The use of a special cabinet, to collect data from different data links and to convert it into one high speed-bus like ARINC-629 will result in a reduction the number of interfaces to just one (dual or triple redundant) ARINC-629 interface within this system.

3.2. Central processing modules

Two major solutions are available: CISC and RISC. The reduced instruction set processors are designed for more computing power than complex instruction set processors. However, the CISC designers try to stay in the race by issuing the same computing power, as in the RISC market. In the area of 20 MIPS, CISC and RISC CPUs are available (e. 68040, 80486, 88k, sparc). The next RISC generation of about 100 MIPS is available (a.e. 88110) and we are waiting for the CISC answer (see figure: 7).

However, there is another point in this discussion which is important for aircraft processing systems. The RISC code requires 2 to 3 times more memory than the CISC code. Our decision in this discussion was to stay with the CISC processors, as long as they have the same range of computing power as the RISC processors. Because of the higher memory requirements in the RISC area, we will switch over when this solution brings much more computing power then the CISC solution. This could be done by placing up to 4 RISC processors, each performing 100 MIPS, on one board (e. 4 * 88110).

For our system, both CISC and RISC solutions are available.

3.3. Global memory modules

The global system memory is required for inter processor *communication and for storing the* processor code.

3.3.1. Communication memory module

This memory module supports the interprocessor communication. This has to be done by working with read-modify-write cycles. This memory could be realized by an additional memory board, or by exporting local cpu memory to the global system bus.

3.3.2. Recourse memory module

This memory module stores the system code for all processors and is realized by special EEPROM devices. With power-on each CPU loads its code from that memory into its local memory and executes it. Executing the code direct from this kind of devices is not effective because of the longer access times. Because of the online programmability of this memory, software updates in the system lifetime are very easy.

3.4. Graphic processors modules

Graphic processors must have special local intelligence to transform graphical commands to screen oriented objects. Because of more growing graphical power in 2D- and 3D aspects we decided on a general purpose architecture (Texas 34020). Graphical transformations are specially supported with a highspeed (20 MFLOPS) floatingpoint processor, which can act fully parallel to the drawing functions. We adapted this architecture for realtime graphics with a double buffering concept and an intelligent color lookup table (CLUT), which also support hardware blinking and overlay techniques. The graphic processor is coupled via a dual ported RAM to the system bus. This supports an asynchronous, highspeed interface with fast update rates (see figure: 8).

3.5. Video and image conversion modules

Because the external video sensors (FLIR, LLLTV etc.) have often line standards, which are different from those of the displays, a conversion to the display line standard is required. Basically we see two different kinds of conversion.

3.5.1. *Video conversion modules*

This is a simple solution (see figure: 9) for linestandard conversion. For example in the AVT program we convert the 4:3 CCIR interlace video signals to the 1:1 50 Hz. none interlace standards of the displays. The interlace signal is interpolated in realtime with just one line duration delay. We support thereby realtime scrolling of a 1:1 window in the 4:3 area.

3.5.2. Image conversion modules

If the conversion (see figure: 10) requires more intelligence, this has to be done by putting the incoming video into a framebuffer, transforming that information to another framebuffer and reading this second framebuffer at the outcoming video line standard. This transformation has to support functions like translation, scaling, panning, rotation, zooming, scrolling and so on. This works with a minimum delay of one frame.

3.6. Video Mixing

The video-mixing module mixes video signals of the same line standard in an analog way. Priority and additive mixing are supported.

3.7. Displays

3.7.1. HDD

In applications for realtime graphics there are some problems with the existing displays on the market. Shadowmask displays have problems with vibration due to the mechanical construction of the shadowmask and are limited in brightness. The existing LCD displays are slower in image changes due to the physical switching time of the transistors.

Because of these reasons we propose the beam index technology (see figure: 11). In displays, using this technology, the phosphor is arranged in vertical

stripes, in a sequence of RGB on the screen, separated by small black stripes, for contrast enhancement. There is no shadow mask which absorbs 80% of the beam energy, so the whole energy is concentrated to the phosphor stripes, which means much more brightness on the screen. The resolution is 512 by 512 triple (RGB) on a 5 by 5 inch display. Because there is no shadow mask, this display has no problems with vibration.

3.7.2. HMD

On the X31A programme we developed a binocular HMD with a total field--of-view of 100 by 40 degrees with a high resolution of 2000 by 800 pixel (monochrome). The distortion of the optical system is corrected with an digital deflection correction within the displays. This ensures a linear screen area with a constant angle/pixel format. The 1 inch monochrome tubes, which feed the optical part, produce high brightness and resolution.

4. SYSTEM SOFTWARE

The basic system software is designed fully in Ada. This gives the application programmer a high-level, abstract, easy-to-use interface to all system functions. Because the highlevel Ada interrupts require a task-entry with context switching on every interrupt, low level interrupts are used within the drivers. This brings short interrupt latency and maximum performance.

In addition to the normal device handling, the graphic processing parts require a more abstract interface. We provide here an interface, where the user defines a virtual screen for every image format (see figure: 12). In that virtual screen the user define the transformation from the aircraft data to the graphical objects in Ada. This virtual screen can be assigned at runtime very easy to a physical display, by a simple Ada command. If the same screen format is to be shown on different displays, the transformation algorithms are shared and the display-file is just copied to more graphic processing units, which increases the overall performance (see figure: 13).

This graphic development can be done on a workstation prior to the availability of the final target system. Several displays are emulated in a X-window environment with exactly the same Ada interface and graphic functions as for that system. So the graphic development can be done on a workstation network with many workplaces, before going to the final hardware (see figure 14).

5. SYSTEM PERFORMANCE

The Ada compilers, which are available today, have the same performance as C compilers due to the sequential part of the language. The performance per CPU has just increased from 3.5(68020/30) to 20 MIPS(68040). This means that the PAH2 BCSG benchmarks are now faster by factor of 7 then those on the 68020/30 CPU.

Besides the synchronous rendezvous mechanisms in Ada, an asynchronous task-to-task communication via mailboxes with semaphores is required. This function is not yet defined in the language and the realization of this in Ada is much too slow. So an realtime operating system has to supply this. The same problem arises with multiprocessor communication. The realtime mother clock quantization in the Ada operating system is now decreased from 20 msec (68030) to less than 2 msec (68040). This results in a finer resolution in task scheduling and synchronization (see figure: 15).

6. DEVELOPEMENTENVIRONMENT

First we started with the Telesoft Ada Compiler combined with the Ready-Systems Operating system ARTX. Because this solution is no longer supported, we have now switched over to the Telesoft-Ada-Compiler combined with the PSOS-M operating system. In addition to ARTX, PSOS-M supports the same task to task communication interface for single and multiprocessing and is an object oriented kernel. This makes it easy for the application programmer to shift tasks from one processor to another without changing the communication to other processes.

The cross and host development tools are available on UNIX workstations (see figure: 16). We use cadres teamwork tools SA/RT for the system analysis phase to build the system requirements model. From this we construct the system architecture model which represents one possible architecture to fulfil the

requirements. In the design phase we work with cadre teamwork Ada, which supports the Ada structure graphs (ASG), defined by Buhr, to construct the software design. From these Ada structure graphs we generate the Ada Source Frame Code. This Ada Frame Code is finally filled with the appropriate Ada statements and then transfered to the Ada-Compiler.

7. APPLICATION EXAMPLES

7.1. AVT

The AVT program is an experimental helicopter programme, unsing a modified BK117, on which flexible, generic avionics have to be installed. The main goal is to build generic instances of this avionics to support specified missions. MBB will do the experimental flights, ESG is developing the operational Ada flight program and we, the Telefunken System Technik have developed the hardware and basic system software for the image and mission computing system. This system contains several interfaces: serial, parallel, ARINC-429, MIL-1553, three intelligent graphic processing units with video conversion and mixing, driven by three CPUs.

7.2 X31A-HMTAS

This system, the Helmet-Mounted-Target-Acquisition-System, is designed for flight simulation. It contains a binocular HMD (100 by 40 degree), a line of sight locator (LOSL) and an Image Management System. This system receives the position of the simulated aircraft, the position of a target aircraft, the line of sight of the pilot and transforms this information in order to display a target wireframe image with 100 3D points, connected via 300 3D-vectors, in realtime (60 Hz.) update rate to the HMD.

7.3. X31A-HDD

One aspect of the X31A programme is to produce a new 3D flight path display with a 3D globe-like object (defined by MBB) to support the pilot in the post stall (low speed, high pitch) range of the X31A aircraft. This is done by our Image Management System which transforms the aircraft data in realtime into a 3D graphical object on a special 5 by 5 inch Beam Index Color-Display.

Aircraft Equipment

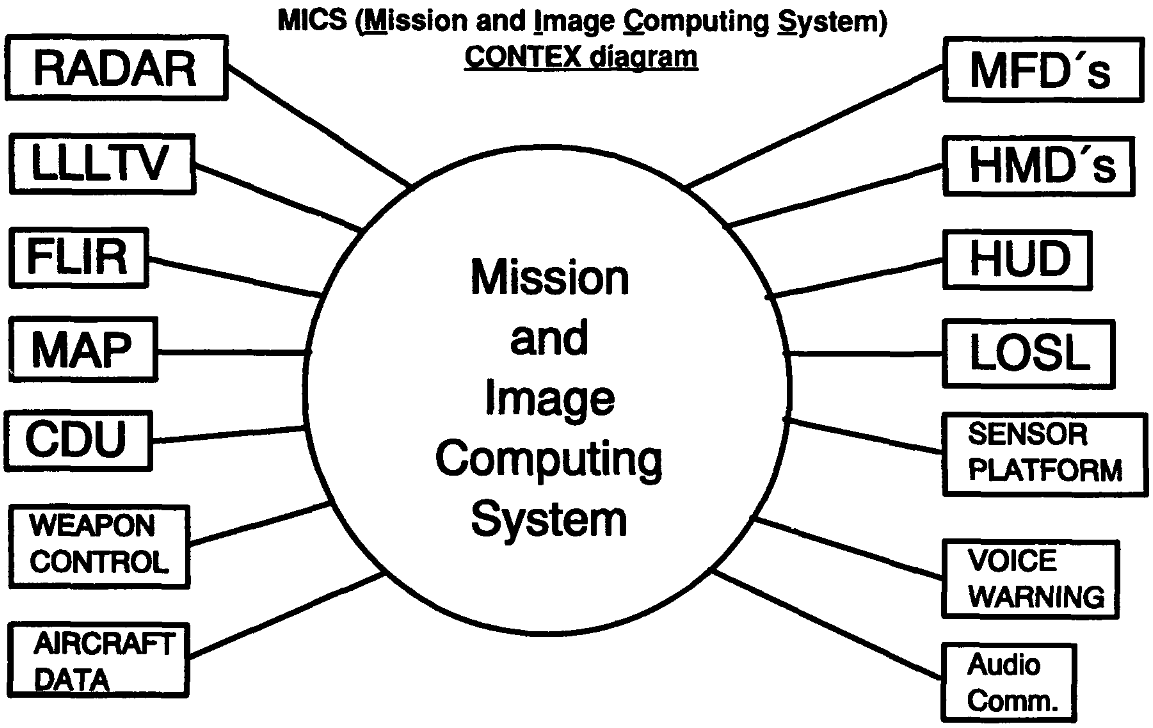


Figure: 1

Aircraft Equipment

MICS (Mission and Image Computing System): bus structures

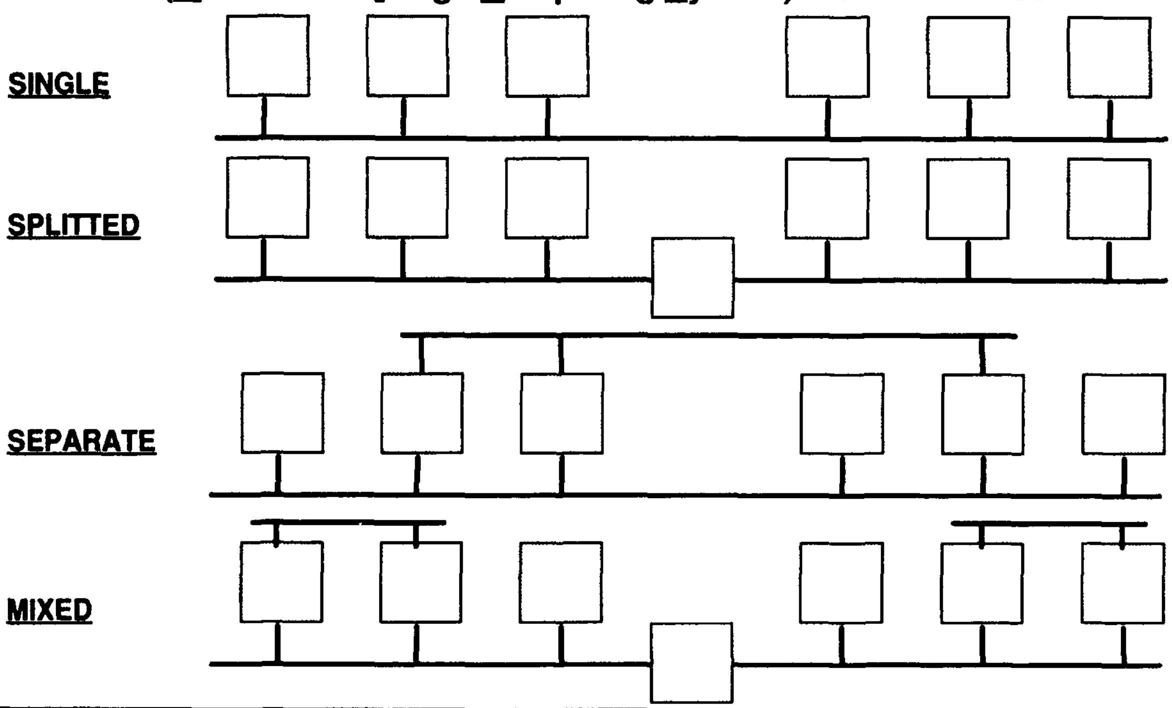


Figure: 2

Aircraft Equipment

MICS (Mission and Image Computing System)
SINGLE bus structure

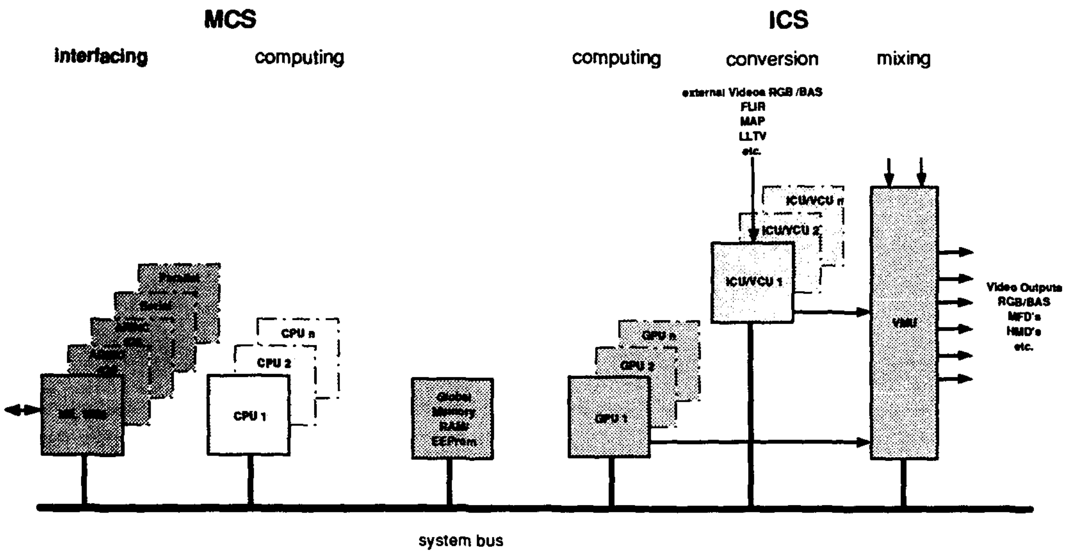


Figure: 3

Aircraft Equipment

MICS (Mission and Image Computing System)
SEPARATE bus structure

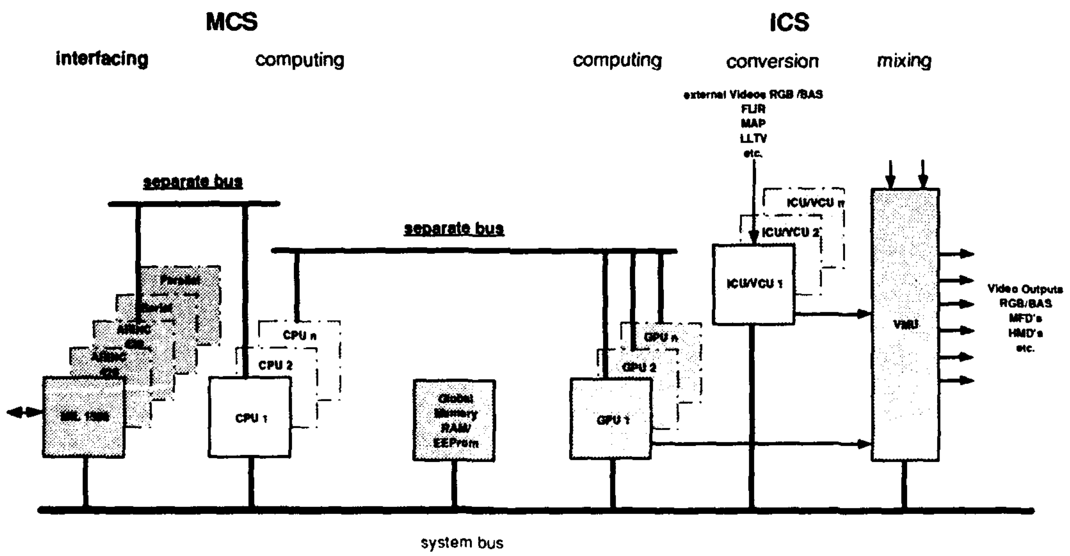


Figure: 4

Aircraft Equipment

MICS (Mission and Image Computing System): SPLITTED bus structure

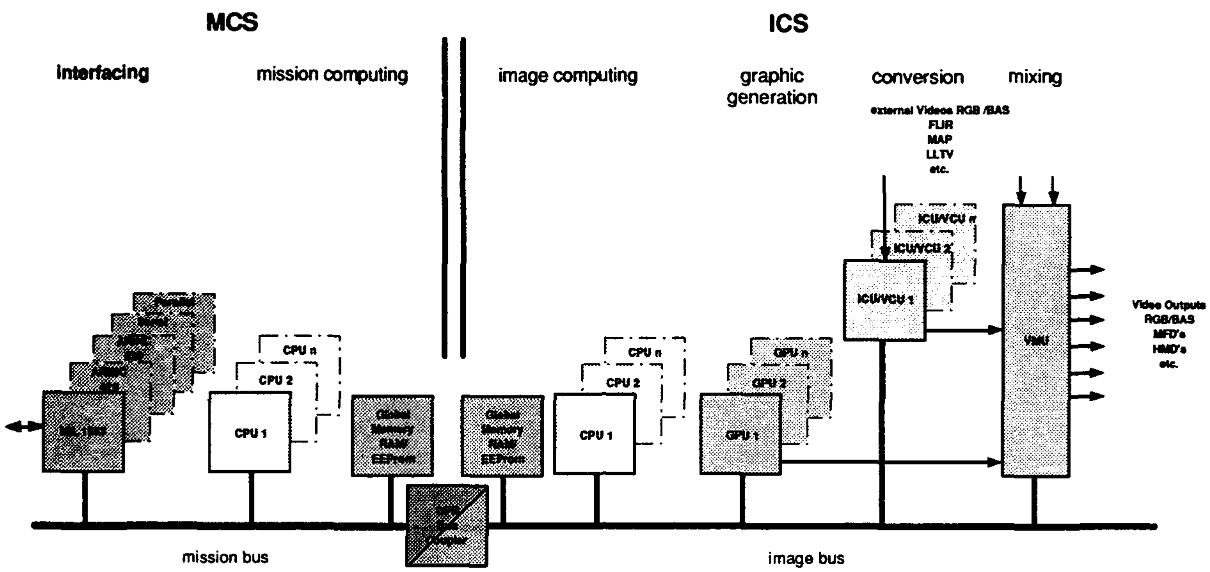


Figure: 5

Aircraft Equipment

MICS Interfaces

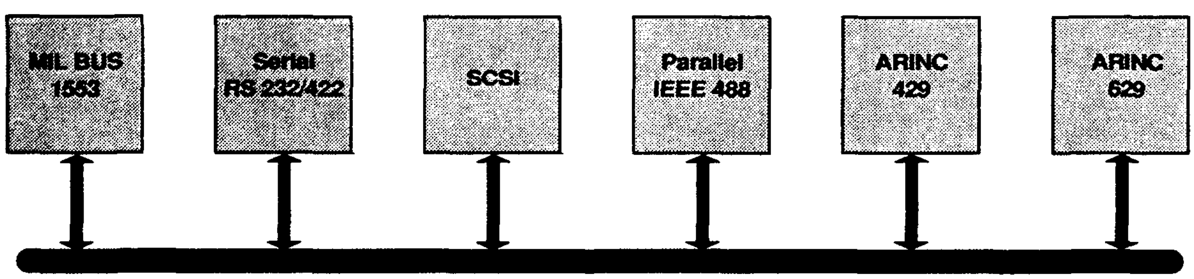


Figure: 6

Aircraft Equipment

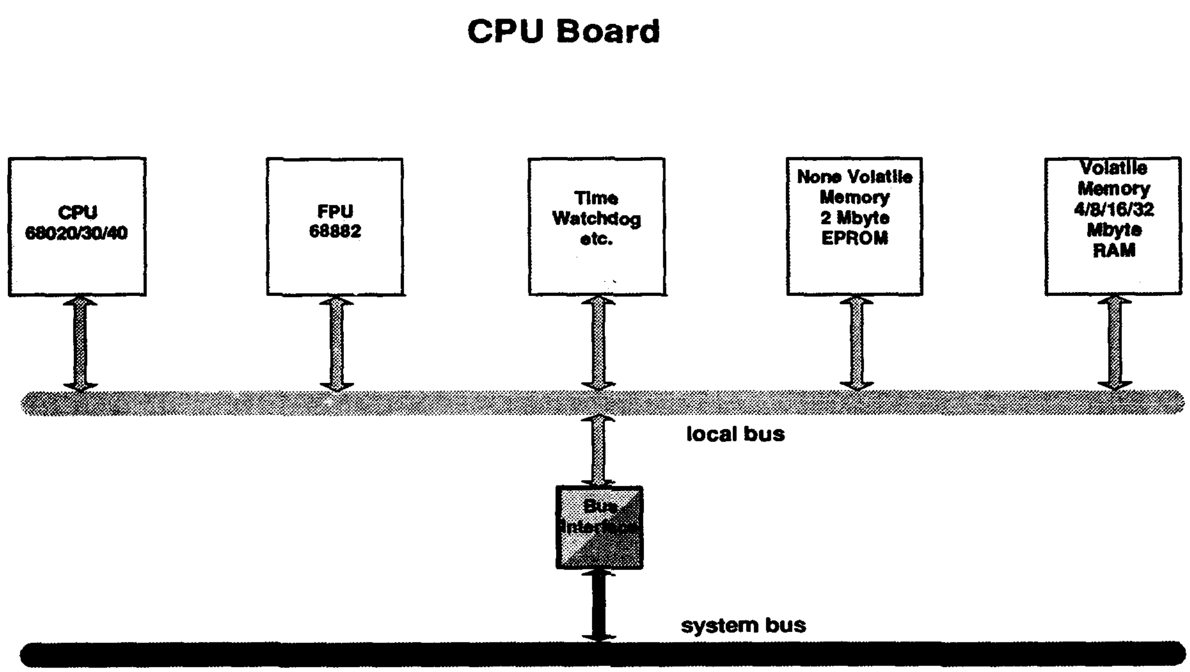


Figure: 7

Aircraft Equipment

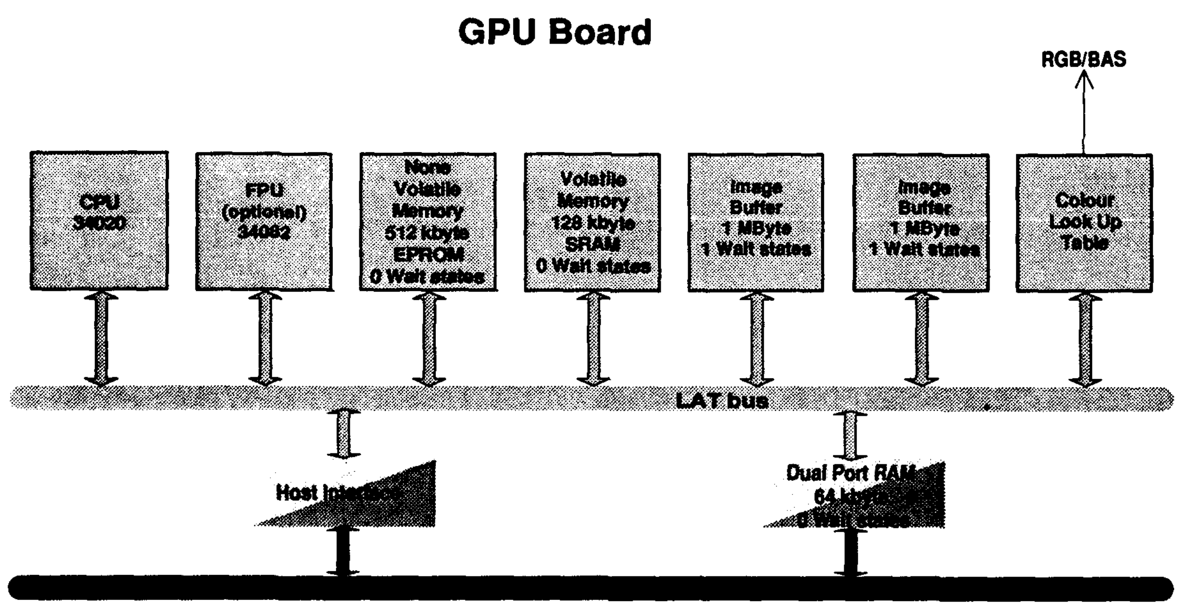


Figure: 8

Aircraft Equipment

VCU Board
(Video Converting Unit)

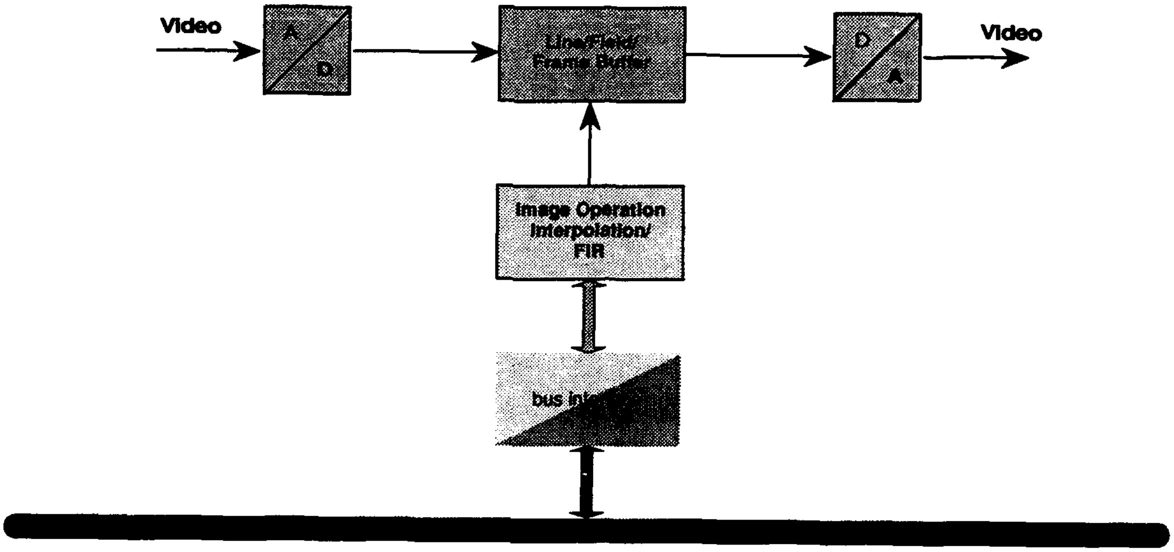


Figure: 9

Aircraft Equipment

ICU Board
(Image Converting Unit)

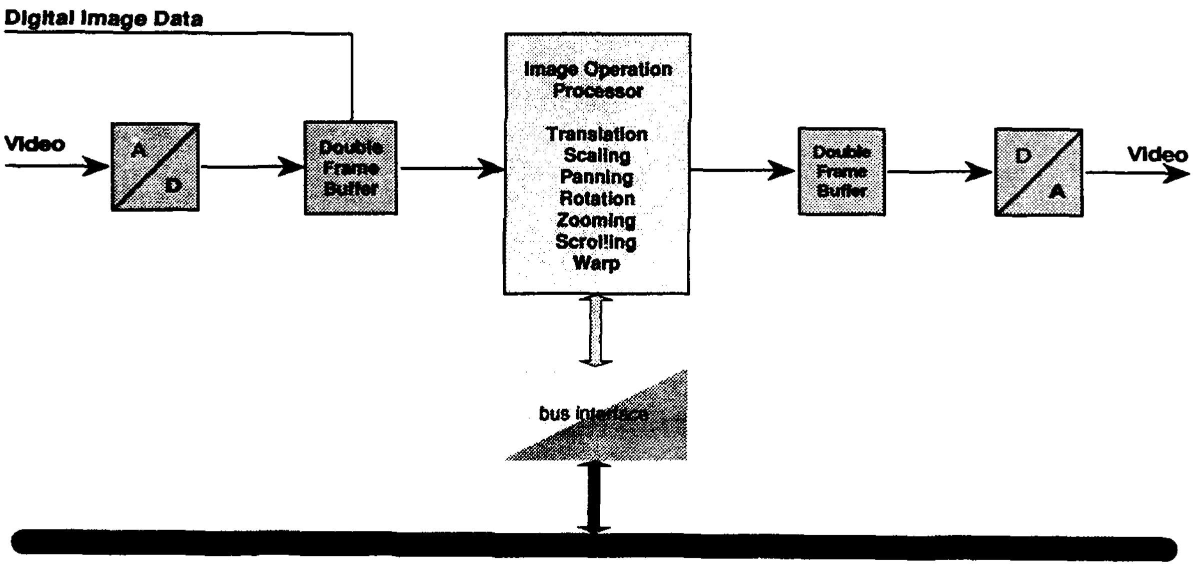
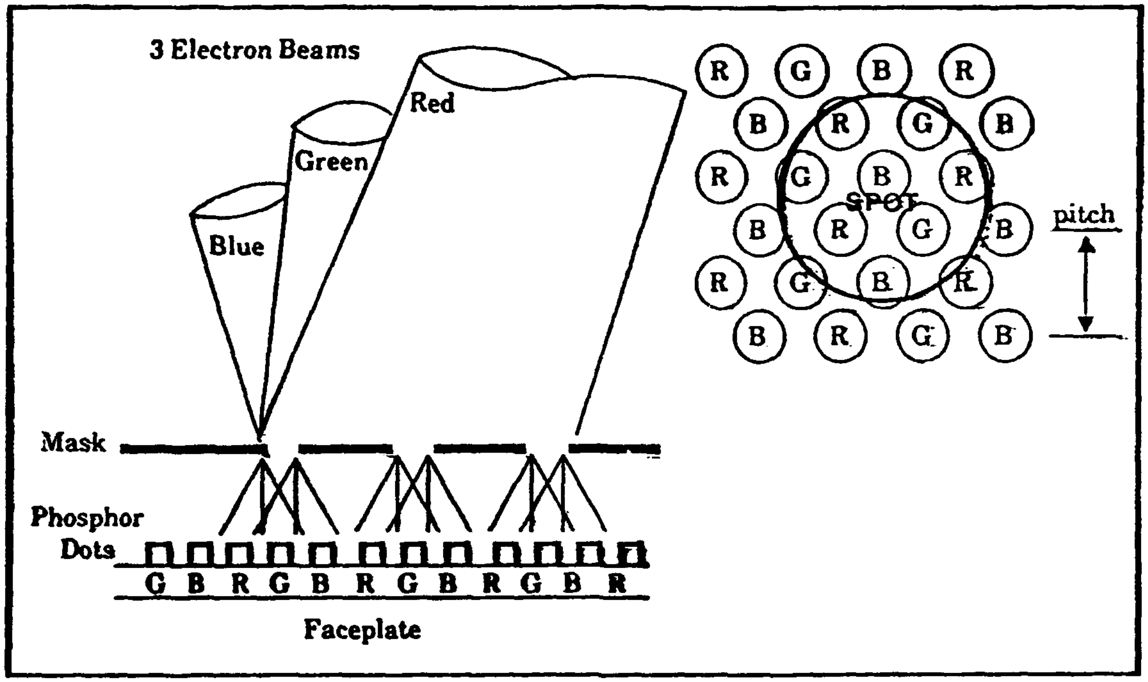
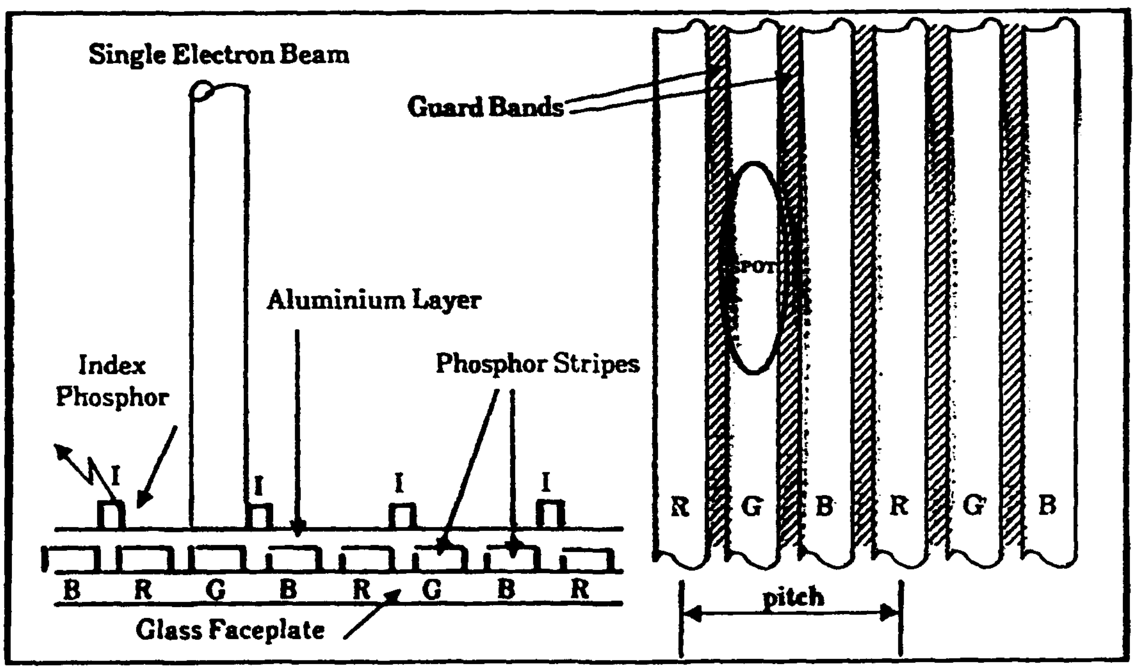


Figure: 10



SHADOWMASK SCREEN STRUCTURE



BEAM INDEX SCREEN STRUCTURE

Figure: 11

Aircraft Equipment

ICS (Image Computing System)
Data Flow Diagram

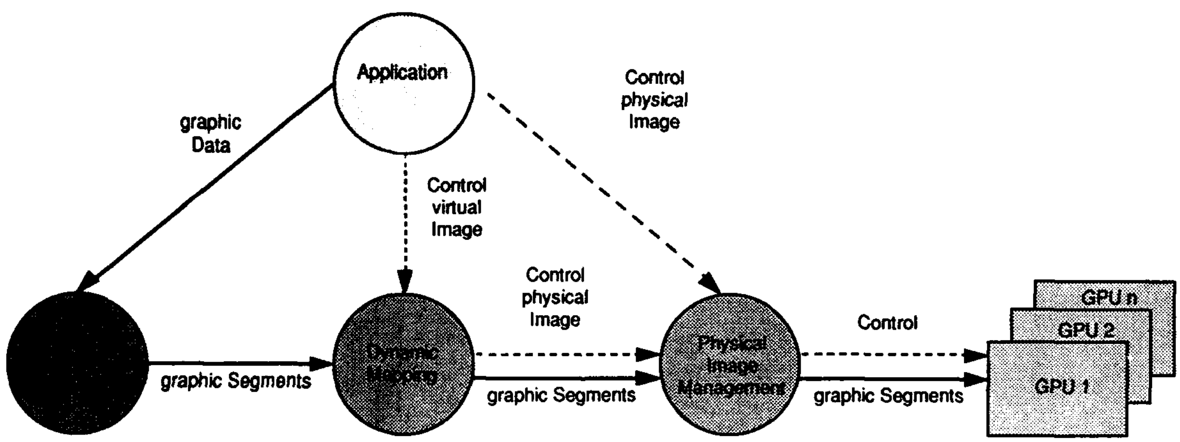


Figure: 12

Aircraft Equipment

ICS (Image Computing System): Software Architecture

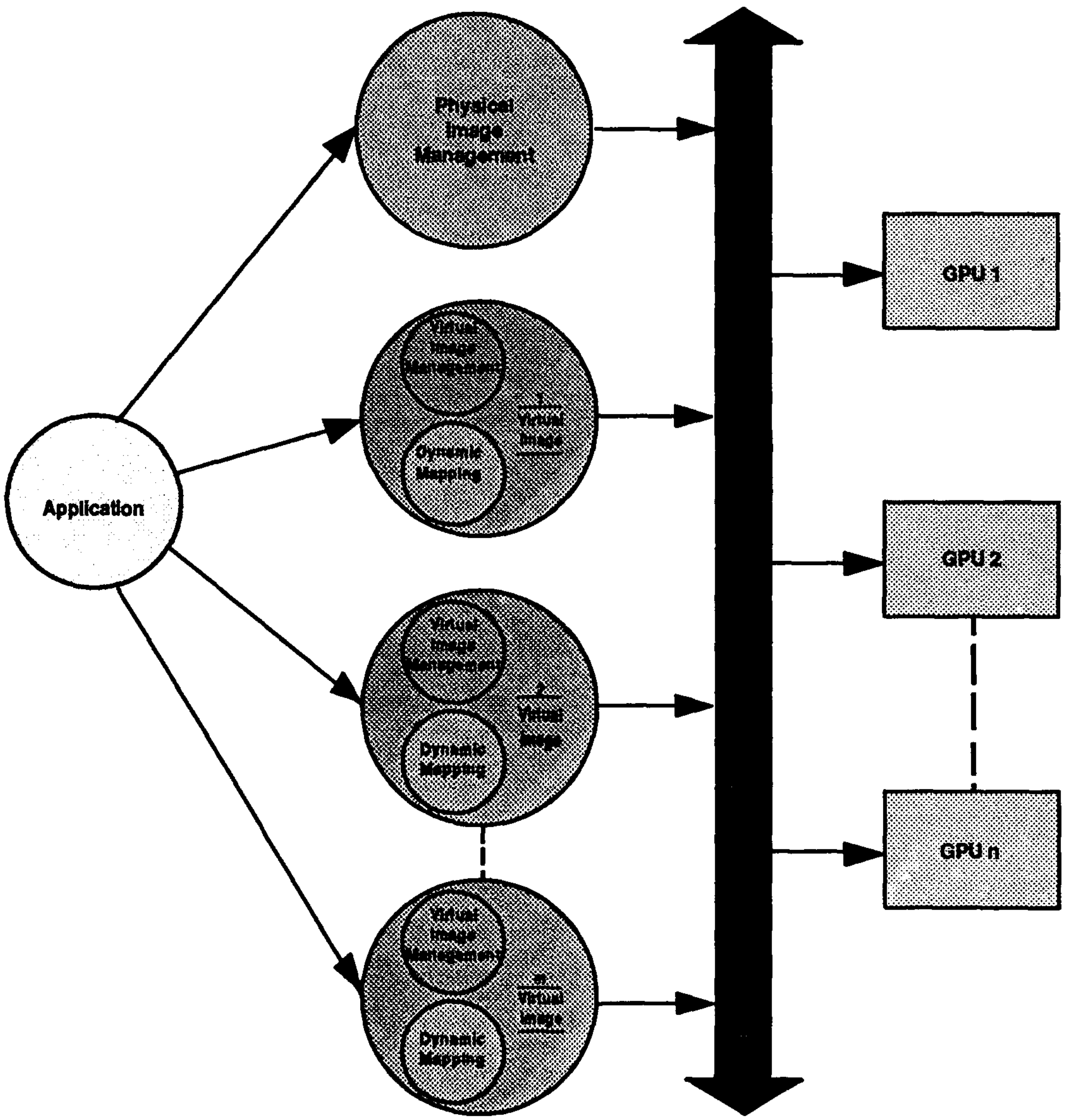


Figure: 13

Aircraft Equipment

ICS Graphic Development

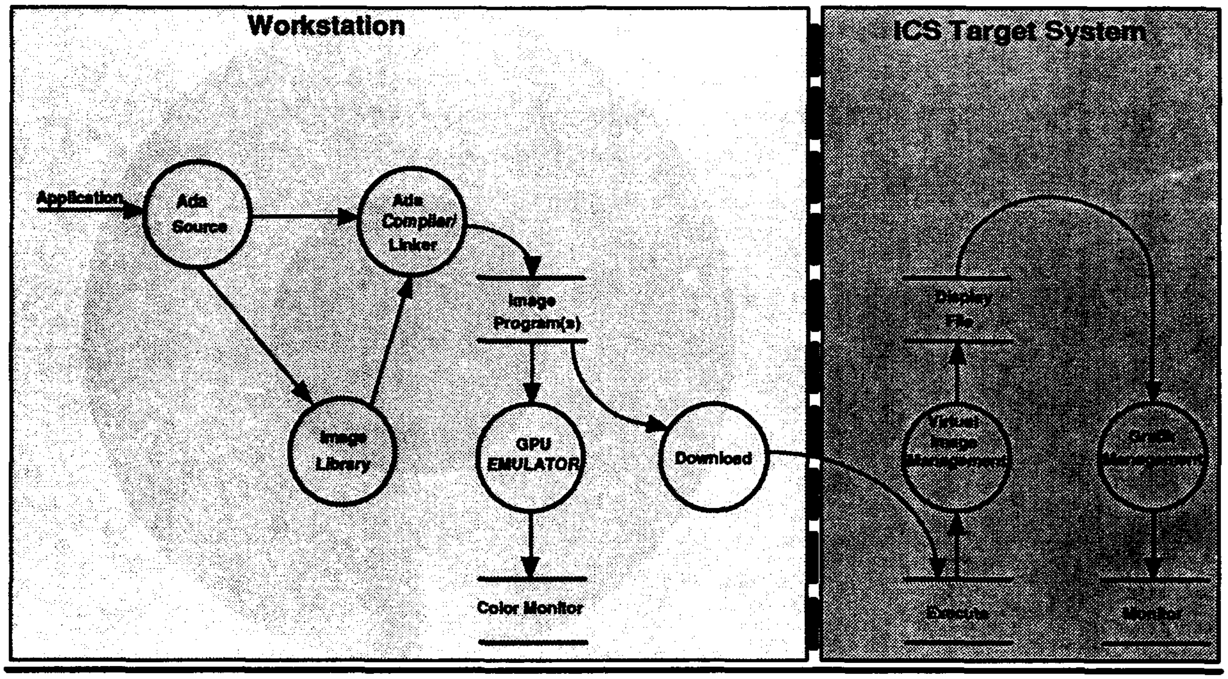


Figure 14

Aircraft Equipment

MICS Performance

CPU:	
68030:	**68040:**
3 Mips	20 Mips
0,16 MFlops	3,5 MFlops

GPU:		
TMS 34020/34082		
10	Mips	(peak)
40	MFlops	(option)
142	Mbit/sec.	Pixbit
1,34	Gbit/sec.	Fill
5	Mpixel/sec	Line draw

Aircraft Equipment

Development Environment MICS

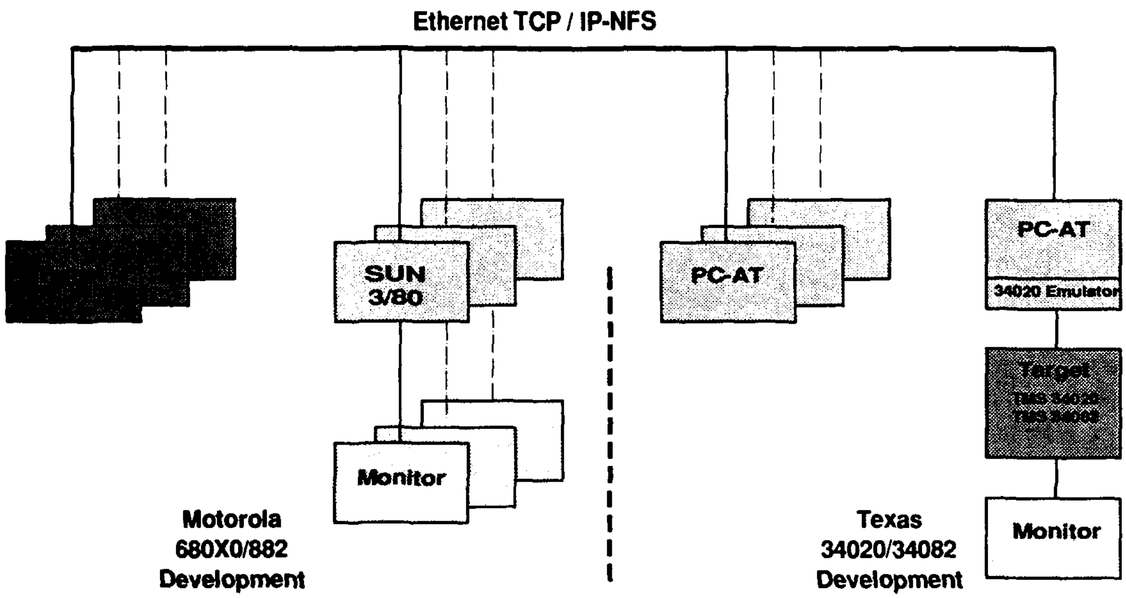


Figure: 16

AIRCREW ACCEPTANCE OF AUTOMATION IN THE COCKPIT

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Abstract

The concept of human-electronic co-operation in the cockpit is synonymous with that of a team. Whether or not team members interact effectively will rely largely upon the pilot's acceptance of his electronic team mate. This paper reports on the attitudes of eight British Aerospace test pilots towards the future of such co-operation. Particular emphasis is laid upon the factors of system function, task allocation and trust. Pilots opinions are examined against a schema of 'Operational Relationships', recently proposed in the literature.

1 INTRODUCTION

The purpose of this paper is to address the issues of trust and acceptance in cockpit human/electronic teamwork. There is a legitimate concern that the strategy of automating all of the pilot tasks which it is technically feasible to automate is unlikely to provide the optimum design for the future human - electronic aircrew team (eg. Hollister 1986). A first defence against this can be achieved by developing a close liaison between the system designer and the pilot population. This should help in the identification of those tasks whose automation would, in the opinion of aircrew, be most beneficial and thus enhance the likelihood of pilot acceptance.

British Aerospace (Military Aircraft) Limited employ a number of pilots to perform test flying on aircraft such as the Harrier, Hawk and Tornado Aircraft. These pilots have many years of fast jet experience in the Royal Air Force or Royal Navy, Fleet Air Arm as well as in other NATO forces. This pool of experience offers BAe an opportunity to gather opinions and gauge initial reactions to the specific and general acceptability of automation.

Questionnaires and structured interviews were used to elicit the views of eight BAe test pilots regarding the functions and philosophies that should drive the integration of automated, semi-automated and human-electronic co-operative technologies in the cockpit. The pilots had a total of 31400 hours of fast jet flying experience (Details are given in Section 1.1). During these interviews reference was made to the concept of Operational Relationships (OR) as described by Krobusek, Boys and Palko (1988). In this schema ten distinct categories of Operational Relationship are defined. These range from OR'A', where the pilot performs the activity, to OR'G'3, where the system may perform the action autonomously. All 10 are listed below in Table 1, and were used after the interviews to categorise responses. During the interviews the concepts were used to prompt the pilots to consider the possibilities and potential for cockpit automation. Throughout this paper opinions are related to this schema.

TABLE 1 'OPERATIONAL RELATIONSHIP' SUMMARY TABLE

OR'A' - The pilot performs the activity
OR'B' - The (relatively straightforward) activity is performed automatically by the system.
OR'C' - The system may remind the pilot if the pilot asks or has authorised such.
OR'D' - The system may remind the pilot
OR'E' - The system may prompt the pilot (with unrequested information).
OR'F' - The system has been given authority to perform function, but with pilot consent.
OR'G' - The system may perform an action only if various conditions are met.
OR'G'1 - The system may perform the action but must concurrently notify the pilot.
OR'G'2 - The system may perform the action, but must notify the pilot when first convenient for the pilot.
OR'G'3 - The system may autonomously perform the action.

The interview techniques required pilots to iteratively address specific elements and aspects of the piloting task, the aircraft's systems and it's operational role. This provided a flexible structure within which pilots could consider existing automation requirements as well as future possibilities. Four general areas were addressed, these were (i) the management of the aircraft systems, (ii) situation assessment, (iii) tactics and (iv) the man machine interface.

1.1 PILOT EXPERIENCE

Details of the fast jet flying experience of the eight pilots interviewed are given in Table 2 below.

Table 2 Approximate Pilot Logs

PILOT	HOURS
1	4700
2	3500
3	3000
4	3500
5	4000
6	3500
7	4200
8	5000
Total	31400

Aircraft flown include:

Tornado (IDS/ADV)
Jaguar
Hunter
Jet Provost
Hawk
EAP
Harrier (+Sea)
F16
Phantom

2. MANAGEMENT OF AIRCRAFT SYSTEMS

2.1 Engines

In general the pilots welcomed engine automation, although they could not easily envisage the potential for automation beyond the fully digital engine controls current in GR5 Harrier or proposed for EFA. Nonetheless, further automation would be welcomed if it maximised opportunities for the pilot to assimilate higher level information by reducing engine system distractors. Particular emphasis was laid upon the desirability of the system performing all pre-flight checks and start-up procedures as there is considerable pressure upon the pilot at this stage in a mission, especially if 'scrambled'. At this stage in a mission pilots wished to only be alerted only if a significant[1] system failure was detected (OR'G'1) believing that self-correcting systems should self-correct autonomously (OR'B'). Following a system failure it was suggested that details relating to the performance penalty of that failure would be required as the pilot may decide to fly in spite of the failure. Thus pilots welcomed decision aiding but did not wish the system to take a FLY/NO-FLY decision.

In general pilots believed that the aim of engine automation should be to provide 'care-free' handling particularly during periods of high mental workload as experienced in low level flight and during emergencies or combat situations. This could only be achieved if the system was of a sufficiently high integrity to engender a high level of trust.

2.2 Fuel and Hydraulic Systems

Current fuel sysetm automation is considered to be at a fairly high level, although past experience has shown the importance of a 'transparent' system that enables the pilot to confidently assume control of the system in the event of a failure. Pilot opinion was entirely in favour of further hydraulic automation, although there was disagreement concerning the OR that should govern these procedures (ranging over OR'F';OR'G' & OR'G'1). Pilots stated that they would wish to sanction (OR'F') any procedure that would affect aircraft performance (eg. moving fuel may affect centre of gravity).

1 'Significant' in this context refers to factors that will affect flight performance or operational capability.

It was suggested that pilots should not have to bother themselves with fuel or hydraulic system operations, although high level information was essential (eg. range, kg. left, undercarriage status)

It was recognised that the requirement for information and sanctioning may be part of the process of developing trust in an automated system.

2.3 Battle Damage, Faults, Malfunctions

In general, pilots did not want to be informed of the technical diagnosis of specific types of battle damage, fault or general malfunction. Rather, under these conditions they wanted the system to reconfigure following OR'G'3 with the qualification that should operational capabilities or flight performance be affected the system should immediately inform the pilot of these new parameters. Again this is an example of the need for decision aiding requirements to parallel those of automation.

2.4 Avionics

Automation of navigation systems, which involve many routine tasks, was believed to be a sensible goal although cautionary reference was made to the integration of early automated Inertial Navigation systems which were found to increase rather than reduce workload due to their poor reliability Although opinion differed upon the level of autonomy (LOA), see also Krobusek, Boys and Palko (**op cit.**) at which specific navigation and other avionic systems should be set, there was general agreement that automated system functions should remain hidden until a pre-defined point at which the system would request authorisation to continue, thus in effect proposing a variant of OR'F'. The point was reiterated that if a function could be automated with high reliability and the effect of this automation had no effect upon the aircraft's performance then the fact of that automation should remain hidden from the pilot. However as recommended by Krobusek, Boys and Palko (**op cit.**) it was agreed that such events be recorded for later, in-flight perusal. This appears to support a special case of OR 'B', but with the qualification that such events be recorded in case they impact upon other factors later in a mission.

3 SITUATION ASSESSMENT

3.1 Automated Sensor Management

All pilots agreed that an automated sensor manager that presented an accurate tactical 'picture' was required, but were sceptical about how accurate such a system could be due to the number of variables that must be considered and the often stated requirement to retain flexibility. Although such flexibility may be achieved by pre-setting the 'goals' of a sensor manager's LOA (eg. be stealthy until x etc) pilots were in general unwilling to accept the concept of L'sOA at a more complex level than that of sophisticated tactical decision aider or mission management aid. Overall the concept of L'sOA as interpreted by pilots at the highest level of authority did not extend to that of dynamic re-allocation of function.

The highest acceptable level was perceived to be that of pre-flight presets of the functions that would be performed by the pilot and by the system. The consensus appeared to be that L'sOA would not (and should not) be reconfigurable in flight. This view appeared to be driven by the realisation that dynamic re-allocation of function and in-flight LOA resets would occur during high workload periods and potentially contribute to confusion during highly inopportune phases of a mission. It seems likely that the most useful arrangement of pilot-system co-operation (LOA) will be predictable because it will be necessary to reduce the occurrence of variations in this relationship during periods when the pilot is integrating the tactical significance of many external variables.

Pilots did agree that a high integrity automated sensor suite would be extremely useful and afford a significant combat advantage for the pilot. Recent developments such as auto-scan centering and auto-scan volume, as used in radar target acquisition, have been enthusiastically received due to the accompanying large reductions in workload. Although pilots believed that automated sensor management and sensor correlation were priorities, they were concerned about the integrity of such a system. Pilots suggested that trust and confidence in such a system could only be brought about through repeated trials in which the auto-sensor's 'picture' was found to be more accurate than that which the pilot had developed from the usual sensor sources. It was suggested that it would be essential to attach confidence levels to the fused and correlated output of such systems. Thus sensed information could be presented in a form such as "I'm 70% sure this is a Flanker". Given these integrity and probability pre-conditions, pilots believed that they would accept sensor management, correlation and fusion at OR'G'3.

3.2 Automated Defensive Systems (DAS)

Defensive aids systems automation was generally considered a good idea, although pilots were concerned that the system could easily be spoofed (tricked into making an error of commission, a false identification of a threat). To cope with this eventuality most pilots believed that an OR'G'1 level would be required but also mentioned that the need to regularly monitor the system to detect spoofing might increase workload. As with most systems manual override was considered essential.

All pilots were unanimously opposed to the concept that the DAS should be linked to the flight control system (FCS) such that automated missile 'Break' procedures could be undertaken without forewarning. Although several rationales were provided, (including those of system error, spoof/annoyance factors and the potential for physical injury) opposition to this proposal was sufficiently strong to suggest that automated FCS intervention 'went against the grain' at a fundamental level. Missile 'Break' related automation was acceptable only at OR'E' (eg. BREAK PORT).

4 TACTICS

There was little agreement concerning the usefulness of automated tactics systems (ATS) but all felt that tactics would be the most complex pilot tasks to automate due to the inherent dynamic and flexible nature of combat. As discussed previously, pilots appeared reluctant or unwilling to conceive of a tactical level of human-electronic co-operation that exceeded that of sophisticated decision aid. Interestingly the point was made that a capability to vary tactical L'sOA (on the ground) may be useful as a pilot training aid for less experienced pilots, although it was stated that the logic and reasoning employed by the system must be very clear. Pilots felt that the optimum role for ATS would be the computation of target engagement paths, missile release zones and paths of egress. Most pilots believed that these functions should operate at OR'E' levels, although some pilots felt that they may wish to allow the system to carry out the engagement through sanctioning system control of the FCS (OR'F'). All pilots agree that regardless of the OR covering target engagement the pilot must perform the weapons release task himself (OR'A'). One pilot could see the full potential for this type of automation stating that should the pilot delegate target engagement procedures to the automated system, this would -

"....allow one aircraft to almost have the capability of two, as the pilot will be able to cover against threats and check systems just as a second crew member would do."

There was a general feeling amongst the pilots that although they could imagine the potential role of an ATS decision aid they would have difficulty trusting the validity of these displays or indeed the information upon which they were based. A typical comment concerned the auto-detection of a SAM site, it was believed that pilot's would wonder (a) is it really a SAM site? (b) has the site run out of missiles? (c) is it just illuminating (spoofing) with it's radar? Pilots felt on the whole that they would be reluctant to trust such a system or the data upon which it made its decisions. Two general accompanying comments were made these were that:

(1) The most useful tactical decision aiding would be the identification of targets (Automated sensor management) together with details of target performance capabilities together with own optimum engagement parameters (eg. intercept speed and course).

(2) The tactical automation 'nightmare' is that the automated aircraft provides lots of clear tactical information to the pilot, but that this information is wrong because the system is being spoofed.

5 MAN MACHINE INTERFACE (MMI)

All pilots agreed that the MMI of automated systems would be critical to aircrew acceptance of such systems. A major concern was that the pilot should be presented with an unambiguous display of 'who' was in control of 'what'. There was also concern that the pilot's desire to be told what the system was doing (OR'G'1) or to sanction automated actions (OR'F') might actually increase his workload.

It was unanimously agreed that there is already too much displayed information in the cockpit for the pilot to reliably intake at periods of high workload and that the proliferation of sensor and weapon aiming systems will exacerbate this problem, particularly in single seat aircraft. Consequently an MMI priority is to reduce the amount of information presented in the cockpit by concentrating on the fused and correlated 'high level' information to be presented to the pilot (eg. "port flap hydraulic failure" or "port flap stuck at 15 degrees" is less useful than starboard roll reduced to **"etc). Thus the pilot should immediately be aware only of the fact and the implications of significant changes within or outside his aircraft. The significance of an event will require clarification through further research, nonetheless significance appears related to the impact of events upon operational performance tactics and safety.

Most pilots agreed that during periods of high workload it would be extremely advantageous if an automated system could prioritise information and present this at a time when this would not be distracting. This is similar to a special case of OR'G'2 in which the concept of 'performing an action' is changed to 'gathering information', rendering the nature of the human-electronic interaction closer to that of human co-operation rather than a simple shift of the locus of executive control.

6 GENERAL ISSUES

A number of general issues emerged from the interviews that have bearing upon the integration of the human-electronic team and the pilots ability to speculate upon such a relationship.

6.1 Operational Relationships

The concept of OR's was easily understood by all pilots, although the pilots varied in the level of the OR they were prepared to allocate to human-electronic teamwork. This in itself may support the concept of 'Pilot Tailoring' a process which would essentially customise a pilot's individual LOA requirements. It was suggested that the ten OR's proposed by Krobusek, Boys and Palko (**op cit.**) could in fact be simplified for the purposes of gauging pilot opinion to:

a) The system does it always (OR'B','G'3)
b) The system does it sometimes (OR'G')
c) The system does it and tell the pilot (either then or later) (OR'G'1,'G'2)
d) The system asks the pilot to be allowed to do it (OR'F')
e) The pilot does it (OR A)

Those OR's omitted from the original schema (OR 'C','D','E') appear qualitatively different from the rest and as such may be better suited to a schema describing levels of decision aiding.

6.2 Levels of Autonomy

In general, pilots had some difficulty imagining functional models of LOA concepts. There existed a general resistance to the concept that human-electronic team co-operation could be redefined whilst in-flight. Although the concept of 'pilot tailoring' was welcomed it was believed unlikely that these parameters would be re-tailored' between missions due to the sheer complexity of remembering another set of variables. A point made throughout all the interviews was that reducing the complexity of aircraft systems must be the goal of automation. Pilots added that they may well not interact with systems that added significant complexity to their task even if those systems could buy an operational advantage. Although Krobusek, Boys and Palko (**op cit.**) argue that the end product of integrating an LOA approach within automated aircraft systems would buy a **"very dynamic range of performance"** for the system, pilots appear more concerned that they should understand exactly what the performance characteristics of all their aircraft systems will be throughout an entire mission, an assumption that does not allow for a wide range of in-flight variations to the co-operative human-electronic team relationship. The LOA concept did receive support from some pilots who suggested that it would provide a useful training and combat aid for the inexperienced pilot.

7 CONCLUSION

Overall, the pilots welcomed automation that would relieve them of tasks during periods of high critical workload and of carrying out mundane and routine monitoring tasks. Whilst there is a degree of mistrust and scepticism concerning the integrity and reliability of future automated systems, the development of such systems are enthusiastically supported as they are seen as the only means by which the pilot will be able to cope with the workload demands anticipated from forthcoming aircraft systems. However, it appears that and effect of this underlying mistrust is that most of the pilots interviewed wish to be presented with information on at least some aspects of the automated decision making processes, a requirement which might actually increase the workload associated with a given task. Interestingly, the pilots opinions were similar to those in the sample reported by Taylor (1988) in venturing that trust in automated systems would not actually develop through the presentation of premises and hypotheses upon which automated decisions had been made but that an individual's trust would develop when the system repeatedly 'got it more right' than the pilot. Ultimate acceptance of highly automated systems would be achieved only when the 'folklore' of trustworthiness generated by reliable systems is passed onto the next generation of pilots.

Many pilots expressed a strong concern that automation will be introduced without fully taking into account the tasks that the pilot performs resulting in a system that will not be used or liked.

The sample of pilots interviewed in this survey was relatively small and hence their opinions should not be considered representative of the pilot population as a whole. Their experience and backgrounds may have tended to encourage a greater caution and apprehension of automation concepts than would be found amongst those pilots who are currently joining squadrons.

Finally, it should be recognised that pilot opinions are just that, they may be wrong, they undoubtedly differ and they will probably change. However, utimately pilot opinion will determine whether or not the human-electronic team members really do work together as a team.

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TIME STRESS MEASUREMENT DEVICES FOR ENHANCEMENT OF ONBOARD BIT PERFORMANCE

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SUMMARY

An important aspect of a pilots situational awareness is the need for accurate real time information on the operational status of all aircraft systems. False and intermittent indications have been a problem with many of the built-in-test (BIT) functions in aircraft systems. These indications result in Retest OK (RTOK) and Cannot Duplicate (CND) maintenance events when the aircraft returns. These types of events account for 35% to 65% of the indicated faults in many Air Force avionics systems. Any false indications put an unnecessary and potentially fatal burden on the pilot during the operational scenario and also consume significant maintenance resources.
Many of these false alarms and intermittent status indications are related to the environmental conditions present at the time of the indication. Time Stress Measurement Device (TSMD) technology offers a means of providing this crucial environmental information to the system's BIT. TSMDs are digital environmental measurement and recording devices in a microelectronic package which can be embedded into a system at the time of manufacture or on a retrofit basis. The information collected and provided by the TSMD can be provided in real time for the on-board BIT to try and discriminate between transient system performance anomalies and hard failures. Thus, only accurate performance status information is reported to the pilot. The paper describes the background of TSMD development, current state-of-the-art in TSMD hardware and software, current applications which address the enhancement of on-board BIT performance and future thrusts in the TSMD area.

BACKGROUND

The magnitude and duration of environmental and electrical stresses play an important role in the useful lifetime and failure of electronics/avionics. Both the magnitude and duration of the stresses affect the performance and failures of the equipment. Some of the major stress sources which have been either identified or postulated as contributors to performance changes and failure are thermal cycling, thermal soaks, vibration, shock, humidity, corrosion and the amount of energy dissipated in the equipment. The effect of these stresses produces changes and damage in the parts, interconnections and physical structure of equipment which leads to failure or altered performance.

Current parameters which are used as a measure of reliability such as Mean-Time-Between-Failures (MTBF) are measured in terms such as calendar time, operating cycles, etc. Thus, when failures occur we are capturing only the effect of stresses on the equipment and not the actual stress history which the equipment was exposed to and caused it to fail. The TSMD is the measurement and recording instrument for the key stress parameters of the equipment of interest.

A TSMD is an integrated sensor package which measures and digitally records selected environmental or electrical conditions which are present at the sensor input. The stored data can be subsequently retrieved for use and analysis in the maintenance and diagnostic process. A block diagram of a generalized TSMD is shown in Figure 1. The data flow through a generalized TSMD starts with the analog signal output of the various sensors being fed into any necessary signal conditioning circuitry and then the signal is digitized in an analog to digital converter. The output of the A/D converter then goes to the controller (microprocessor) for any necessary manipulation or compression and then is stored in nonvolatile memory. A real time clock is used to provide a timing input to the controller and a data port to the controller is used as a user interface for retrieval of stored data and for programming the TSMD.

DISCUSSION

TSMD Module Development

Beginning in Fiscal Year (FY) 86, the development of a TSMD module was begun by Rome Laboratory. This contractual program with Honeywell was jointly funded by RL and the Productivity Reliability, Availability, Maintainability (PRAM) and Generic Integrated Maintenance and Diagnostics Systems (GIMADS) Program Offices of the Air Force's Aeronautical Systems Division at Wright-Patterson AFB OH. A TSMD module using off-the-shelf components was designed, developed and qualified for use in a flight data collection program utilizing A-10 and A-7 aircraft. The module, which was approximately 3 cm x 8 cm x 16 cm, measured and recorded parameters for temperature, vibration/shock, relative humidity, prime power voltage and corrosion. The TSMD module was cable connected to a battery pack utilizing sealed lead acid cells which furnished power for continuous TSMD operation and recording. The data from the TSMD module was removed through a serial port which was used to drive a RS-232 interface through a small adapter box into a handheld computer.

Internally, the TSMD circuitry is divided into a sensor/analog circuit card assembly (CCA) and a digital CCA. The TSMD module was designed to sample the environment through use of a suite of sensors consisting of a thermocouple, humidity sensor, corrodible resistor, a single axis accelerometer and rectifier.

Excursions of the avionics environment beyond user defined limits for humidity, vibration/shock, and aircraft power were recorded in memory "bins". The TSMD measured accumulated vibration exposure above two field adjustable thresholds in each of four different frequency bands between 10 and 2000Hz. The number of shock events greater than a field adjustable threshold were recorded. The accumulated exposure time above a field adjustable threshold for relative humidity was also recorded. The aircraft prime power voltage was monitored and accumulated exposure time for both high and low voltage conditions beyond predefined limits were recorded.

During each day, any excursion of a set parameter beyond its prescribed limit caused the corresponding bin to be incremented. At the end of the day, each bin contained the number of times the limit was exceeded for the day. The bin counts were saved and then cleared to start the next days collection.

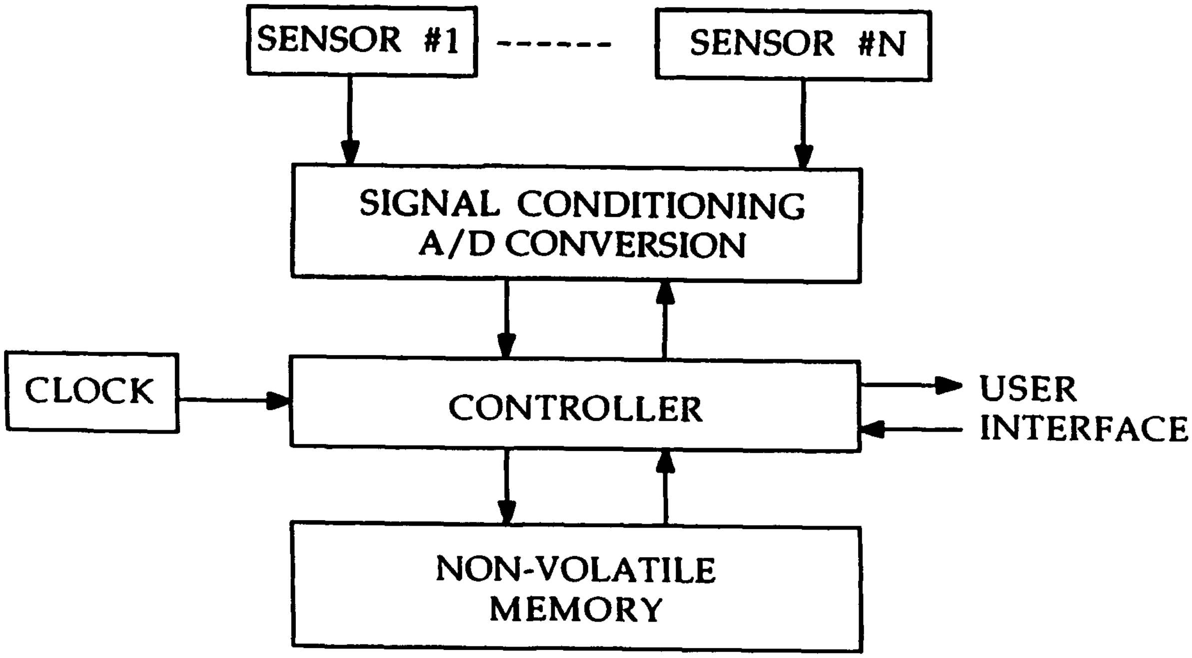

FIGURE 1
TSMD BLOCK DIAGRAM

Temperature data was sampled every fifteen seconds and recorded. Also, a log of power on and off events is included in the temperature file. In this way, a complete record of the temperature profile seen by the TSMD was recreated during data analysis. However, because the memory space required to store a temperature point each fifteen seconds was prohibitive, the data was compressed to reduce the data storage memory size requirement. The compressed data takes the form of best fitting ramps and lines to the individual data points. Resolution of the compressed temperature data was approximately +/- 2.5^{o}C.

Sensing of corrosive atmosphere was provided by a detector consisting of two mild steel strips. One strip had a protective coating and served as a reference while the other was exposed to the atmosphere and exhibited an increase in resistance to indicate the relative amount of corrosion.

The realization of this development was the installation of ten of the TSMD modules in five A-10 aircraft and five A-7 aircraft (Ref 1). This was the first time that a device of this type has been used to collect data on operational aircraft during normal sorties. Collection of data of this type prior to the use of a TSMD usually required much larger instrumentation and a dedicated aircraft for testing. A typical temperature profile for a day including two sorties is shown in Figure 2. The actual flight times from the squadrons records are added to the graph to provide a comparison with the power on time.

Micro TSMD

A natural progression from the module was to an integratec unit the size of a microelectronic package. RL began development of a Micro TSMD in FY88. IITRI-Honeywell and Westinghouse competed in a design definition phase (Phase I) for development of a hybrid device which would be self-contained (including sensors) to provide temperature, vibration, shock, and voltage monitoring. This led to a full-scale development phase (Phase II) of the Micro TSMD. The Micro TSMD development is being sponsored by the Air Force Reliability and Maintainability Technology Insertion Program (RAMTIP). IITRI-Honeywell is under contract to complete the design of the Phase II Micro TSMD. The Micro TSMD is suitable for mounting on a circuit card in an LRU. The first insertion of the Micro TSMD will occur in systems supported by Warner-Robins Air Logistics Center (WR-ALC) Robins AFB GA.

The Micro TSMD is physically a 1" x 2" flatpack with leads on 50 mil centers. Power consumption is about 100 milliwatts while powered from the host (recording data). When host power is unavailable, recording activity is determined by the availability of a button-cell battery. With a battery present, the real-time clock is maintained and mechanical shocks are recorded. The recording of mechanical shocks is useful for determining if units were mishandled during shipping or installation of the host card.

Retrieving stored data is accomplished by an RS-232 link to a debrief computer (laptop model). The data will be transferred to disk and analysis can take place at the depot or other maintenance level in the logistics process. Programming options and parameters can be changed while communicating with the TSMD. The TSMD can also be reset by the debrief computer.

The Micro TSMD is a hybrid device. It contains two hybrid substrates, a digital hybrid and an analog hybrid. The digital hybrid contains a 87C51 CPU, EEPROM memory, a real-time clock, A/D converter, crystals to support the clocks, and glue logic.

The analog hybrid contains the temperature sensor, a piezoelectric accelerometer, the transient monitoring circuit, differential amplifiers, voltage regulation, a power on/off detection circuit, and voltage monitoring circuits. The vibration sensor provides a transfer function which will reduce aliasing of the sampled signal. Further filtering of the vibration signal is contained within the analog hybrid.

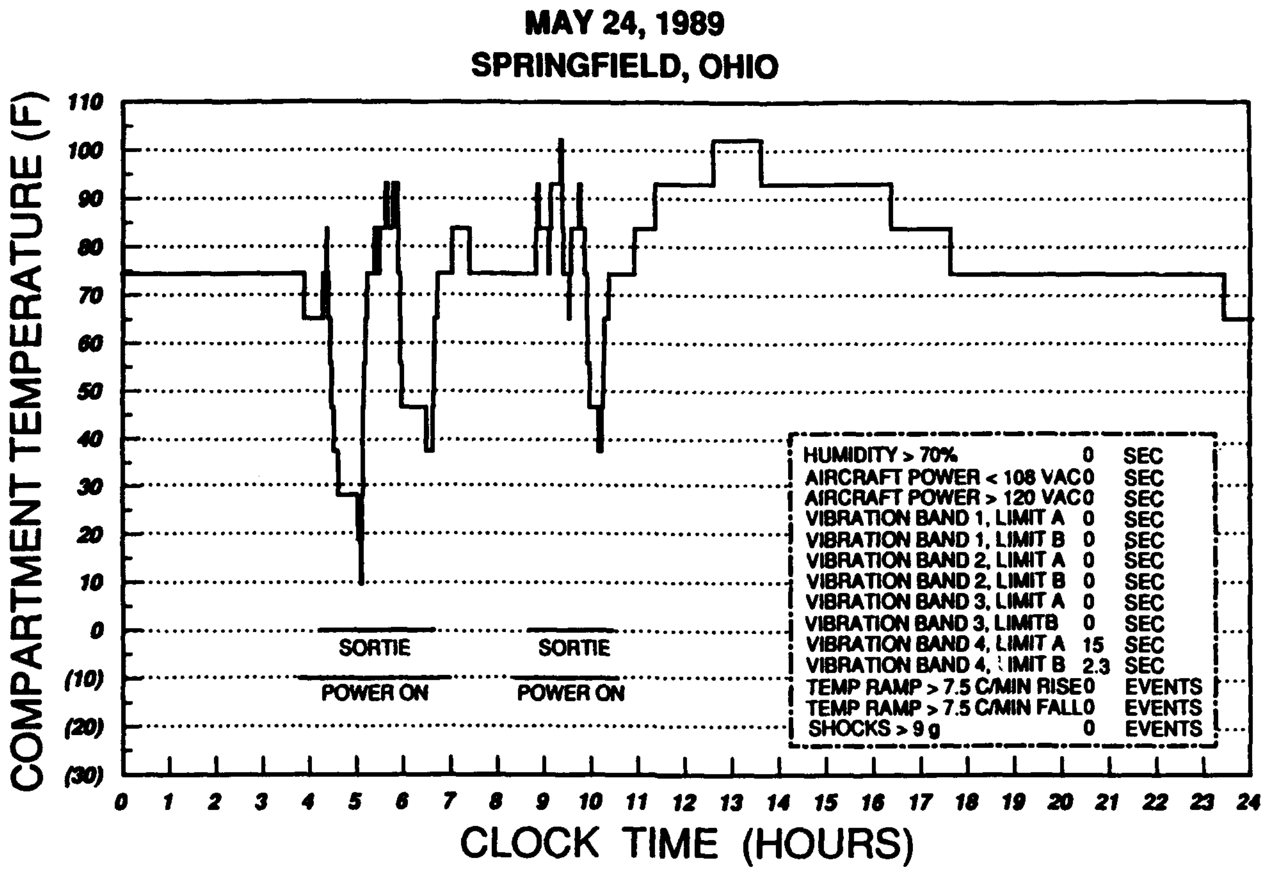

FIGURE 2
TSMD STRESS PROFILE FOR A-7

The sensors and given digital hardware allow recording of parameters with the range and resolution shown in Figure 3. Software programmable options allow these parameters to be recorded in many ways.

- TEMPERATURE: -55°C to 125°C RANGE, 1°C RESOLUTION
- VIBRATION: +/- 3 Gs MAXIMUM, 20-2,000 Hz PASSBAND, -24dB, OCTAVE ANTIALIASING FILTERING
- SHOCK: 3.0 G POSITIVE THRESHOLD, -3.0 G NEGATIVE THRESHOLD, 1MS duration, + 25 Gs MAXIMUM SCALE
- DC VOLTAGE: 0-10 V RANGE, 10 mV RESOLUTION
- VOLTAGE TRANSIENTS: 17 V AND 40 V POSITIVE THRESHOLDS, 4 V NEGATIVE THRESHOLD, 1 MICROSECOND MINIMUM TRANSIENT DURATION

FIGURE 3
MICRO TSMD SENSING PERFORMANCE SUMMARY

The Micro TSMD software is designed to make efficient use of the available memory for storage of recent data collected and historical data. Also, the software will allow the user to change threshold limits, tolerance regions, sampling rates, memory allocation, time stamp resolution, and maintenance text data. Examples are shown in Figure 4.

- TIME-LINE DATA ROLL OVER
- TEMPERATURE SAMPLING PERIOD
- TEMPERATURE AND VOLTAGE RECORDING TOLERANCE
- VOLTAGE DEAD BAND
- VIBRATION SPECTRUM SCALE
- INTERNAL OR EXTERNAL SENSORS
- CLOCK BATTERY AND SHOCK BATTERY
- TIME-LINE DATA FILE ALLOCATION

FIGURE 4
SOFTWARE OPTIONS

The program which controls the Micro TSMD is approximately 36K x 8 long. Part of the program, 16K x 8 is stored in the 87C51 EPROM with the remainder stored in the EEPROM. Scratch-pad memory built into the 87C51 is used for many purposes. The main thrust is to use the CMOS scratch-pad ram for frequently changing data (sampled signals, flags, variables, etc.) while using the EEPROM to store processed data. This technique is used to reduce the write cycles to the EEPROM since EEPROM has a wear out proportional to the number of write cycles.

The user may want to emphasize one environmental parameter recording more than others. As part of the setup, the user can define how memory "files" are used to customize the Micro TSMD for stress data recording. A file is a 2K x 8 segment of EEPROM memory. The main types of files are maintenance text, stress data recording, peak event record and post record analysis.

Stress data recording consists of temperature, voltage, shock and voltage transient recording. The number of files allocated for each of these data types may be specified by the user depending on his requirements and limited only by the amount of memory in the Micro TSMD.

Peak events are recorded in a file and stored with a time stamp. The number of peak events which can be recorded in a file depends upon the resolution of the time stamp specified by the user.

A Fast Fourier Transform is performed on the vibration data immediately. Records of time at overall RMS levels and time at g^2/Hz levels are retained. Temperature stress data is reduced to total time on temperature, temperature cycles, and temperature ramps for both rise and fall.

Information in a stress data file is also analyzed to gather information from it that would be useful to the user. Analysis on that data to reduce it to a final form will free up memory and allow subsequent stress data to be recorded over older data without losing the stress history. The types of post record analysis include temperature and voltage.

Voltage measurements are recorded in two tables. One holds total time at voltage (5.0 volts nominal). A second table holds the number of on-time durations.

A capability exists in the Micro TSMD to accommodate remote sensors. This flexibility allows the user to add enhanced sensors as they become available. Additionally, spare analog-to-digital channels are brought out to pins which allow user defined signals to be processed by the Micro TSMD. (Ref 2)

Smart BIT

Concurrently with the development of TSMD technology, Rome Laboratory has been investigating enhanced techniques for incorporation into a system's BIT for reducing the number of false removals. These investigations have been carried out under the title "Smart BIT". Smart BIT is best thought of as an adjunct to the actual functional test, but it could easily be integrated into a singular BIT function. Current BIT technology often places 100% confidence on the results of a test, even though these results could be biased by the behavior of other units or temporarily influenced by transient environmental conditions. Incorporation of an N-out-of-M filter can improve the condition to some degree, yet even it can be easily misled. Smart BIT goes beyond these simplistic approaches to include a more robust reasoning process that looks for information in the pattern of faults and incorporates knowledge of time, the environment, and other information outside of the functional realm of BIT. The principal techniques identified for which software was developed and demonstrated were Information Enhanced BIT, Improved Decision Rule BIT, Temporal Monitoring BIT and Adaptive BIT.

For Information Enhanced BIT, decisions are based on information internal to the unit under test (UUT) as well as other external sources. These could be environmental monitors or information concerning the operational mode of the platform or the health of other systems. Improved Decision Rule BIT incorporates a structure suggestive of an expert system format to increase the robustness of the BIT decision process. Temporal Monitoring BIT uses Markov modeling techniques combined with a finite state machine representation of unit health to monitor performance over time. Adaptive BIT makes use of two general learning paradigms: k-nearest neighbor and neural network back propagation. In both cases, the BIT report in question is plotted into an n-space defined by the various parameters of interest, such as vibration, GO/NO-GO, airspeed, duration of failure, etc.

An important item to note is that no Smart BIT technique may suffice for a given equipment selection. Careful attention must be made regarding the proper selection, prioritization and integration of Smart BIT techniques based on a sound understanding of the BIT and mission needs of the unit-under-test to which they are being applied and to the specific tailoring of the techniques to that application.

Research has been done to define the degree to which TSMD and Smart BIT need to share information and to identify pertinent characteristics of that data to be retained in memory. It is apparent that TSMD data should be available at three levels of temporal resolution: uncompressed in the temporal vicinity of a possible failure for use by onboard BIT, compressed for duration of a mission, and statistically characterized for equipment and missions to be used in long-term trend analysis.

A scenario for the operation and use of TSMD and Smart BIT technology can be postulated. During a mission the TSMD portion is continually recording stress profiles in a wraparound fashion, replacing old data with ore recent measurements, the older values being data compressed and stored in long-term memory. The TSMD will also detect specific stress profiles that could damage equipment and note their occurrences in the long term memory. When stress data is needed by either Smart BIT or maintenance equipment, this information is retrieved from the long term memory.

When a failure condition is detected by the smart BIT, the TSMD is asked to return relevant stress data. Depending on the criticality of the system to the mission and flight safety, the Smart BIT will continue to analyze both the functional test data stream and the TSMD output. If necessary, this process may be performed off-line while a spare unit is switched in place of the one in question. If a decision is made to declare a unit faulty, information relevant to that decision process will be stored local to that unit's nonvolatile memory for access later by other maintenance processes. (Ref 3)

Fault Logging Using Micro TSMD

The next step in the field validation of TSMD for enhancement of onboard BIT performance is being accomplished under the Rome Laboratory program "Fault Logging Using Micro TSMD". Westinghouse is the contractor for this program which got underway in June 1991 and is scheduled to be completed in December 1993. The objective of this program is to adapt a Micro TSMD type design to log environmental stress data at the time of occurrence of a fault in a selected system Line Replaceable

Unit (LRU) and demonstrate these capabilities in a flight data collection program using a fielded Air Force System.

The LRU selected is from the forward radar in the B-1B bomber, this LRU has a past history of a significant CND rate and it is believed that this is related to transient environmental conditions during flight. Forty B-1B aircraft will be equipped with Micro TSMD devices for a twelve month flight data collection program. The parameters which will be measured by the Micro TSMD are temperature, vibration and shock, cooling air supply pressure for the LRU and power supply conditions for the LRU.
The environmental inputs are placed in several data structures within the Micro TSMD which include:

1. Recent Stress Data
2. Historical Stress Data
3. Peak Stress Data
4. Fault Window Data

The largest data structure is the Recent Stress Data component. Two (2) hours of environmental data is maintained in this data structure. The environmental data includes: temperature data from two sensors sampled at most once per second, voltage data sampled at once per second, FFT information calculated from vibration data, shock and voltage transient information, and power on/off events all with the necessary information to relate this data to real-time.

Historical Stress Data is a segment of the nonvolatile memory map where stress information from the Recent Stress Data component is compressed. The Micro TSMD was designed to manage data gathering and storage in excess of 30 days; therefore, the Historical Stress Data structure was developed to maintain information with less resolution until the Micro TSMD could be debriefed.

Peak values are maintained for parameters of interest such as temperature, voltage level, voltage transient, shock magnitude, and peak power measured in each vibration FFT frequency band. These values are time tagged as events and stored in nonvolatile memory.

The primary processing algorithm of the Micro TSMD is the Fault Window which time tags environmental stress data before, during, and after a fault or overstress event and places it in nonvolatile memory. The Fault Window consists of several data structures that share a time stamp as a key field. If a system failure is detected or if a software set environmental threshold is exceeded, the data resident in the cyclical buffer is time tagged with the BIT fault code, and is placed in nonvolatile memory. The Fault Window has an adjustable interval. Sampled data is placed in the cyclical buffer at frequencies ranging from 1 to 8,000 Hz. As such, when a fault or overstress event occurs, the cyclical buffer is halted. Depending on the width of the Fault Window which is software programmable, the processor counts backward N address locations and places N words of cyclical buffer memory data in nonvolatile memory. The same process occurs for data after the event. Cyclical buffer memory to sustain an adjustable window from 30 seconds to 5 minutes has been implemented in the Micro TSMD. (Ref 4)

Each time that the host LRU's BIT indicates that checkout or removal by maintenance personnel is required after a mission, the Micro TSMD will be debriefed. Debrief is accomplished through a spare test connector on the LRU into a palm held computer. The debriefed Micro TSMD data will be placed in a data base with all available failure and maintenance data relative to each indicated LRU failure. This data will be analyzed in an attempt to correlate BIT detected failures, the type of failure and the recorded environmental data surrounding the failure. In previous Air Force conducted tests there were indications that a link may exist between equipment failures and environmental stresses for this LRU. The twelve month data collection and forty aircraft sample size should provide a statistically stable basis for correlation of data.

If there is a quantifiable correlation between recorded stress data and BIT detected failures for a significant number of occurrences, then this will provide a sound basis for further development and testing of onboard TSMD/Smart BIT techniques. Algorithms can be developed for onboard testing which could significantly reduce the number of indicated failures during operation. Currently a program that would conduct a requirements analysis phase for integration and field testing of intelligent test/Smart BIT techniques with TSMD technology is being initiated.

CONCLUSIONS

TSMD technology's feasibility has been demonstrated. The TSMD module showed that a digital environmental measurement and recording device could be developed which provided very useful information in a field environment within the memory, processing and data compression constraints of current technology. The Micro TSMD is a significant leap forward in physical size, which permits its use on circuit cards in LRUs or Line Replaceable Modules (LRMs), and enhanced operational performance. This enhanced performance permits greater precision in data measurement and recording and the potential for its integration into the BIT methodology for the host LRU. "Fault Logging Using Micro TSMD" is a critical step in the development of future onboard BIT performance enhancements. It should provide the evidence that many BIT detected failures are not hard failures, but soft failures. This means system performance was temporarily out of tolerance due to transient anomalies in some aspect of the operational environment. Also, it should indicate those intermittent hard failures which may be activated only by a specific environmental stimulus. Concurrently with the development of the TSMD technology, Smart BIT techniques have been investigated and developed. All the technology is in place and the plans made for a major jump in the performance of an onboard diagnostic capabilities. The benefits are fewer pilot distractions from false BIT indications, better aircraft availability and reduced maintenance costs.

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Discussion

QUESTION R.LITTLE

Could you give details on the number and location of TSMD sensors required to cover a complete avionics system?

REPLY

Several alternatives have been considered. The current micro TSMD (2.5 * 5 cm) is too large to fit onto every card. Currently one device per box or LRU is being utilised with up to 4 temperature sensors and 1 accelerometer which can be either internal or external to the TSMD. Suggested locations for the sensors include input and output cooling air temperature, any thermal problem areas and LRU chassis acceleration normal to the circuit cards.

There are current plans to make the micro TSMD even smaller (approximately 2.5 * 2.5 cm) so that it becomes more feasible to put one on every circuit card or LRU. These TSMD's will have the capability for additional external sensors and more flexibility for communicating with system diagnostics.

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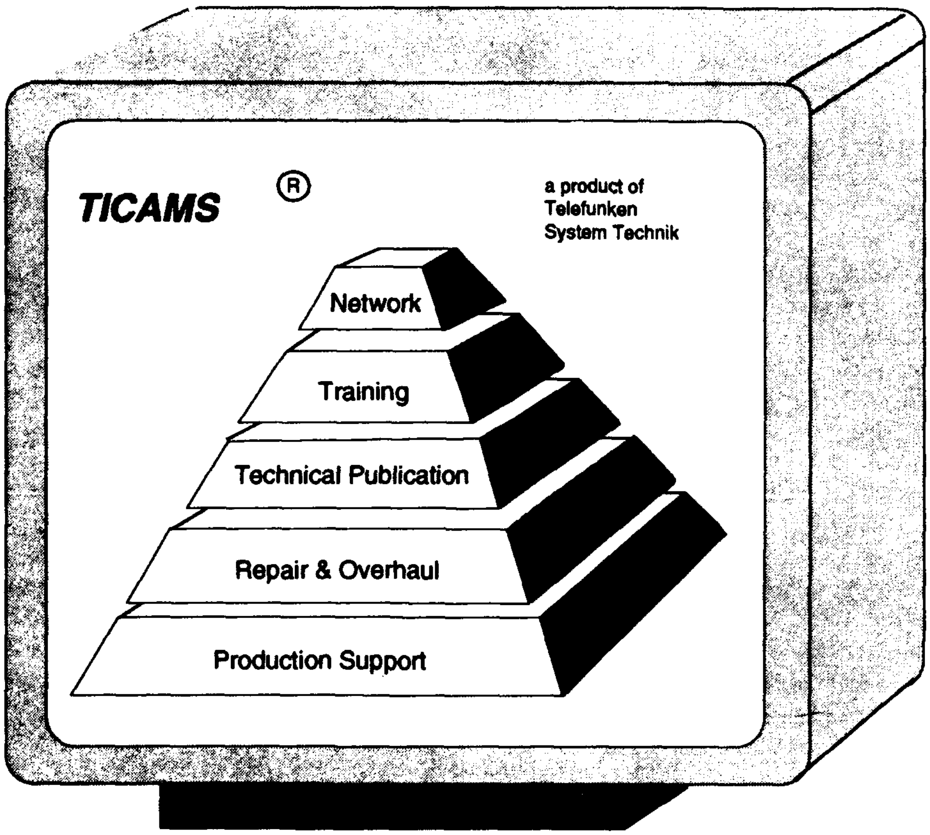

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SUMMARY

In view of ever decreasing budgets, the Aspect Life Cycle Cost (LCC) of a product is gaining in importance.

Telefunken Systemtechnik has been working for more than 10 years in the area of Integrated Logistic Support with the aim of minimizing the LCC for new products. TICAMS is one result of this work.

TICAMS is a general test system for development, production and utilization phases. This universal concept automatically provides the practical and theoretical knowledge of each phase whilst minimizing costs. In doing so, the overall system requirements with regard to the user are supported by TICAMS thus leading to cost minimization in the utilization phase.

TICAMS supports the user in conducting maintenance and repair work, optimizes essential tests and diagnosis procedures during the test procedure, and supports the user during each of the work stages by means of a comprehensive user interface and information system.

TICAMS uses test strategies specified to the product which is to be tested and maintained, and works with an expert system for optimizing the diagnosis and test.

TICAMS works with an integrated instruction and user-guidance concept which facilitates a comprehensive training program - from industrial training or on-site user training to regular refresher courses for the user.

Therefore TICAMS uses electronic documentation. This electronic documentation is partly conveyed in the form of video sequences, thus reducing the costs required to compile the documentation.

TICAMS was developed according to the principle that only a single test system, which covers all of the user's requirements and is able to be networked to other systems, can reduce the LCC.

CONTENTS

LIST OF ABBREVIATIONS

AITEST	Artificial Intelligence Test, a product of Intelligent Electronics Ltd.
CIROS	Computer-Aided Integrated Documentation RetrievalSystem on Optical Storage Media, a Product of Messerschmitt-Bölkow-Blohm
GUI	Graphical User Interface
Hyperdoc	Hyperdocumentation, a Product of GECI International, S.A.
ILS	Integrated Logistic Support
LCC	Life Cycle Cost
MBB	Messerschmidt Bölkow Blom
TICAMS	Telefunken Integrated Computer-Aided Maintenance System
UUT	Unit Under Test
VSS	Video Support System, a Product of Telefunken Systemtechnik

1. Introduction

Maintenance is a term which is of particular significance today. The meaning of this concept, however, largely depends on personal interpretation and understanding. This is due to the variety of individual activities and responsibilities and their specific motives and objectives. Interest or disinterest in this area varies considerably, from the purely operational motive and the financial aspect to personal motives on the customer side as well as on the manufacturer side. The main concern of all parties involved is to protect their own interests.

There is only one means of balancing these different considerations and this is in the form of dialogue. A cooperative dialogue between all partners involved is necessary to pursue the objective of minimizing the cost factor for the system/equipment utilization phase.

This dialogue must be started in the initial system-definition phase since the maintenance strategy, with all of its positive and negative aspects, is already being devised in this early cycle phase.

The growth in technology and complexity of equipment has increased the need to use excellent teams consisting of a large number of specialists to plan how the equipment is to be put into operation. The ability to provide self-help with regard to repair and re-commissioning work has had to be reduced.

The technical developments have only gradually allowed technicians to exchange complete units instead of repairing them. This has led to an extreme need for capital investment due to higher numbers of turn around units.

This awareness of higher capital requirements initially had no

direct consequences. There was sufficient money in the budgets. Today monetary conditions have deteriorated in a dramatic manner. In order to be able to introduce and to utilize the necessary equipment, not only the procurement costs are carefully considered today but the "follow on cost of service life" also plays an important part.

The use of "Integrated Logistic Support" resolves the problems listed above in that the entire effectiveness of the product must not only be defined according to its operational requirements but also to the degree of

- reliability
- test characteristics
- maintenance characteristics

involved. These logistic design elements largely determine the entire life cycle costs of the equipment.

Requirements regarding

- maintenance personnel and skill level
- test equipment
- spare parts
- repair and overhaul work

directly depend on the logistic engineering process and its results.

Our Telefunken Systemtechnik Integrated Logistic Support department guarantees the integration of logistic engineering and support elements into the system design. They are already equal partners to system development within the concept, definition and early design phase.

With more than 10 years experience within the field of logistic engineering our products are designed under the scope of performance and logistic supportability with equal priority to reducing life cycle cost.

Figure 1-1 shows the development cycle of an ILS product. The result is a logic support system which is designed according to logistic-engineering requirements.

Telefunken Integrated TICAMS is a logistic support system

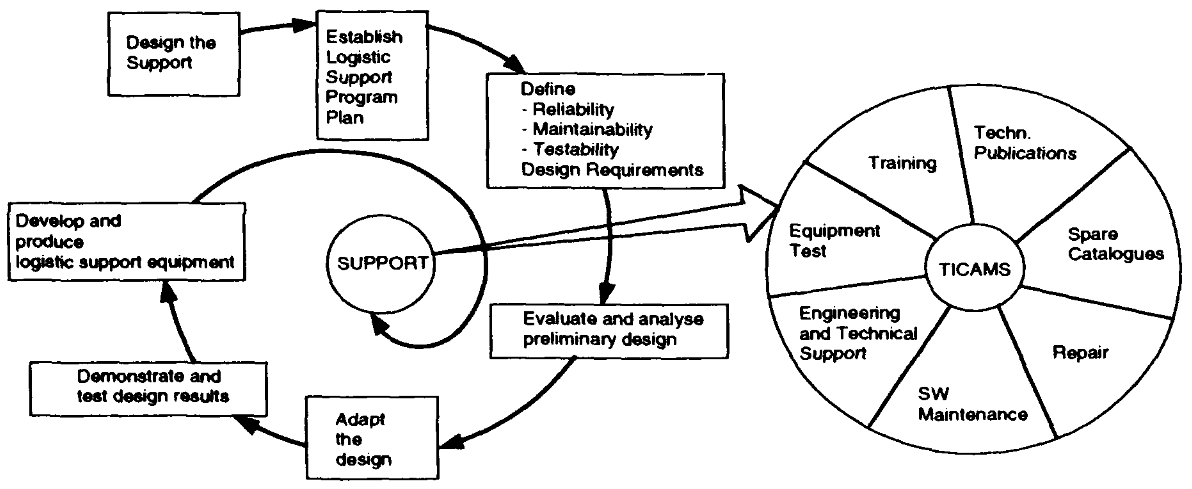

FIGURE 1-1 TICAMS IS AN ILS PRODUCT

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2. Objective of TICAMS

Figure 2-1 shows indeed that the major part of the total LCC is concentrated in the production and series phases, the type and occurence of these costs are however established in the initial development phases of a prod''ct.

The primary objective of T\CAMS is to minimize the costs in the utilization phase.

Figure 2-2 shows in an example of Test and Repair Activities the variety of activities which must be performed by the user during this task. These activities are extremely personnel-intensive and therefore cost-intensive.

TICAMS is implemented at this point and supports the entire process during the utilization phase. Furthermore, TICAMS provides feedback to the previous development phases.

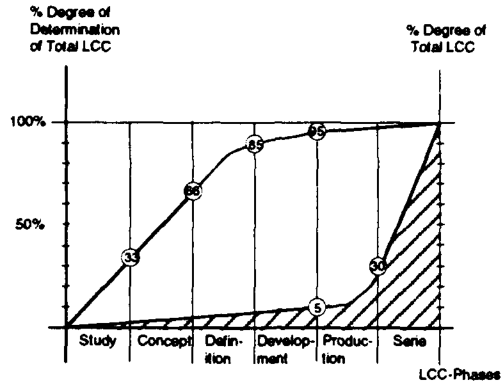

Figure 2-1 Life cycle costs 20508 004

2.1 Repair Support

Repair work usually requires access to different software repair systems, e.g.:

- configuration control for the equipment
- access to warehouses for spare parts and to check their availability
- ordering of spare parts for conducting repair work
- checking of the service life of the system
- entering the actual data for the system in quality-assurance systems

The objective of TICAMS is to provide all of the essential repair work by means of the test system.

2.2 Optimizing the Test Procedures

Tests are usually performed on the equipment while the repair work is being carried out. These tests can also be extremely costly and time-consuming and may end in diagnostic routines.

TICAMS aims to optimize the complete test procedure, (including any necessary diagnostic routines) with regard to the time/cost aspect, therewith taking into consideration the specific features of the equipment.

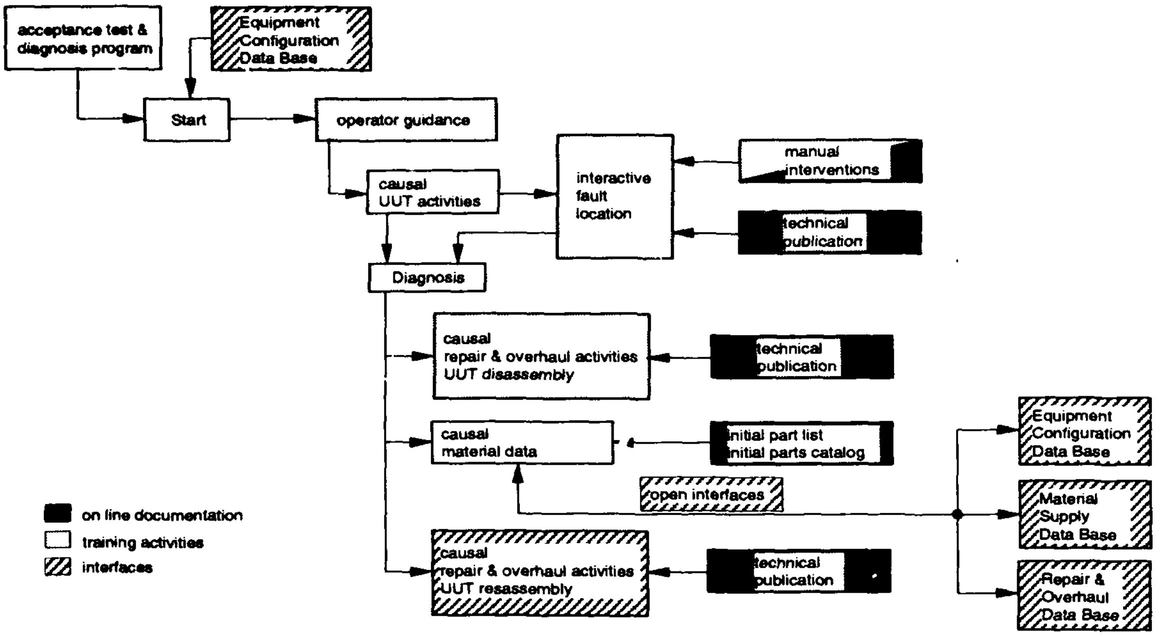

FIGURE 2-2 TESTER-relevant activities during the utilization phase

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2.3 Support by Means of Technical Publications

Technical publications (i.e. documentation) are required for all activities with the equipment. These include the following:

- functional description of the equipment
- instruction manuals
- maintenance manuals
- repair manuals
- spare parts catalogues (illustrated with text)

This documentation is required for both the equipment and the test and support systems.

The problem for the user is that he must always have this documentation at hand if, due to overall complexities, he requires certain information and secondly, he must know where to find the missing information.

The high cost of compiling this documentation poses a further problem.

TICAMS aims firstly to provide the user with all of the required information in the form of electronic documentation. Secondly, the user should be presented with the well-ordered relevant information for the respective process. Thirdly, TICAMS aims to present this comprehensive information to the user not in a 1 : 1 ratio but with a higher information density (e.g. display of logically annotated photographs or videos). This represents the sole means of reducing the total documentation costs.

2.4 Comprehensive Training Program

Every user of equipment or test system must receive appropriate training and instruction.

This instruction or training must take into consideration the skill level of the trainee and the activities which he will subsequently perform. Depending on the type of training required, this will either take place in an industrial centre or directly with the user.

Additional specific training material is often compiled to conduct these instruction and training courses.

TICAMS aims to provide the user with an optimum user guidance system for the test system and to supply all of the essential information for the respective process directly to the concerned position. TICAMS will provide this information independent of the skill level of the user. An additional training mode is intended to provide the user with any information beyond the scope of the respective process and enable him to access the required instructions for the test system and equipment.

These facilities can be used for initial training purposes and later, as a refresher course.

Training documentation, therefore, can be kept to a minimum or, in some cases, may not be required at all.

2.5 Phase Overlapping

As described in sections 1 and 2, a product must be regarded in terms of phases.

The testing and maintenance aspects cannot be taken into account during the production phase or later with the user.

The aim of TICAMS is to examine in an initial development phase the testability of the machines by using rapid prototypes and knowledge from expert systems. Weak points can thus be easily eliminated when the machine is being designed.

Furthermore, by implementing TICAMS in the production process, important characteristics of the equipment can be collected and incorporated into the test system. This information can then be supplied on-site to the TICAMS user.

On the other hand, by incorporating report and analysis systems, any weak points in the machine can be detected and, by networking the systems, can lead to design changes thus constituting a full cycle (see figure 2-3).

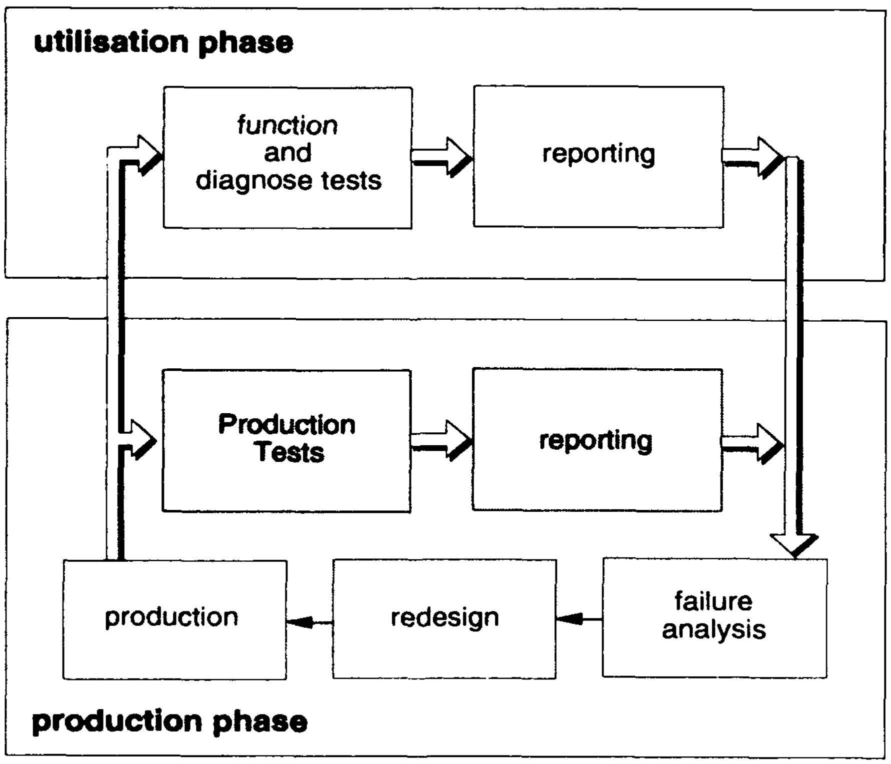

Figure 2-3 TICAMS Phase Overlapping between Production and Utilization 20508 005

3. Features of TICAMS

3.1 Graphics Iser Interface

TICAMS features a state-of-the-art Graphics User Interface. The system can currently be run under UNIX (X-11 window) All of the Graphics User Interfaces have been created using the OSF Motif and can be operated with a mouse. The menu system features both pop-up and pull-down menus. The entire Graphics User Interface (GUI) is of modular design and thus can be easily modified to meet particular customer requirements.

When the system is initialized, the Graphics User Interfaces are configured automatically, according to the user's requirements. The selected configurations are taken from resource files. This also facilitates subsequent adaptation for new software tools, such as electronic documentation tools for example (see section 3.5). In this way, the Video Support System (VSS), for example, can be integrated subsequently into the system by simply modifying the resource file. The existing system therefore does not have to be modified.

3.2 User Guidance

One of the main problems with complex test systems is that they are difficult to operate.

TICAMS provides the user with a comprehensive user guidance system using Graphics User Interfaces (GUI).

After the test system has been started automatically, the user is presented immediately with a log-in GUI. When logging in, the user is assigned a skill level; this enables the degree of support the user will receive.

A total of 3 different levels is recommended in practice:

- master level: for the experienced user who requires minimum support
- assistant level: for the average user who has received the standard training
- beginner level: for the beginner who has yet to receive training for the test system.

Each user can select a level lower than his assigned level when logging in, so that users who have not worked with the test system for a considerable length of time can reacquaint themselves quickly.

TICAMS can be supplied in two versions

- Development Version
- Runtime Version.

Unlike the user in the Development Version, the user in the Runtime Version does not have access to the operating system. All of the functions within the test system can only be operated via GUI. Similarly, the GUI cannot be manipulated. Even the classification and administration of the users who have been authorized to log in are performed via GUI.

In the Runtime Version this prevents

- manipulations of the system
- incorrect operation of the test system.

After the user has logged in, he can access all of the functions of the test system, such as

- user administration (provided that the user is authorized to do so)
- system configuration (provided that the user is authorized to do so)
- data bank for previous test (test history)
- reporting system
- self-test and automatic calibration of the test system
- specific tests
- electronic documentation

The user is guided within each function by means of the GUI from which he can select subfunctions. For example, he can view, edit, print or create backups of the information in the test history data bank for all or just certain test subjects. The same facilities are available in the reporting system. Naturally, backup copies can be reloaded into the system so that older information can be reviewed on all of the test systems at any time.

The user receives continuous guidance during the test in order to perform the test and execute the corresponding commands. An appropriate set of help texts can be selected for each process from the electronic documentation.

Each user can call the electronic documentation immediately after he has logged in. He can thus access all of the configured documentation tools and the corresponding documentation. In this training mode, the user can view the documents freely on the screen.

3.3 Strategies

The term strategies is used here to describe the various ways in which a function test or diagnostic procedure can be performed if a fault occurs. A distinction is made, therefore between a test strategy and a diagnostic strategy.

3.3.1 Test Strategy

All of the test programs in TICAMS are of modular design. A test program consists of test modules which in turn comprise individual test sequences. Each test sequence is a complete measurement conducted on a test subject and thus represents the smallest test which can be performed.

This structure enables the user to choose:

- to perform a complete test program (using all of the test modules)
- to perform an individual test module.

The user can then select various evaluation modes within these different test modes

- display all test results on the screen
- only display test results on the screen if a fault occurs
- display none of the test results on the screen

In addition, the user can define a break point to change the evaluation mode. He can also form group tests for individual test modules in the test mode.

All of the test modules in each of these groups are performed in sequence.

If no faults are found with the specimen, further strategies are not required. The user can call individual test modules as required in order to perform individual tests. He must only ensure that a complete test program is performed once so that the specimen can be marked as "GO", i.e. fault free.

Since the specimen must be released as "fault free" as quickly as possible, for cost and time reasons, the "complete test program" is used as the default test mode in the test system.

If a fault is found on the test subject, however, the time required until the subject can be released after it has been repaired must be taken into account. In doing so, it is necessary to take into consideration that a diagnostic result for complex modules is not always 100 % accurate (for example a diagnosis result could show that one specimen module is responsible for 60 % of the fault and another for 40 %).

If the complete test program is then performed after a module has been replaced in the specimen, the fault may still be present. In this case, the "wrong" module was replaced and a complete test program was performed in vain. In order to overcome this problem, TICAMS provides the

- Verification Test

TICAMS starts automatically at a test sequence which should have changed from "Fail" to "Pass" after the module has successfully been replaced. If this is the case, TICAMS starts the complete test program automatically. If the fault is still present, TICAMS starts the next diagnostic routine automatically. TICAMS generates the appropriate information for the verification test from the data bank of previous tests.

3.3.2 Diagnostic Strategies

There are several ways of locating a fault in the test subject once it has been detected (see Fig. 3-1).

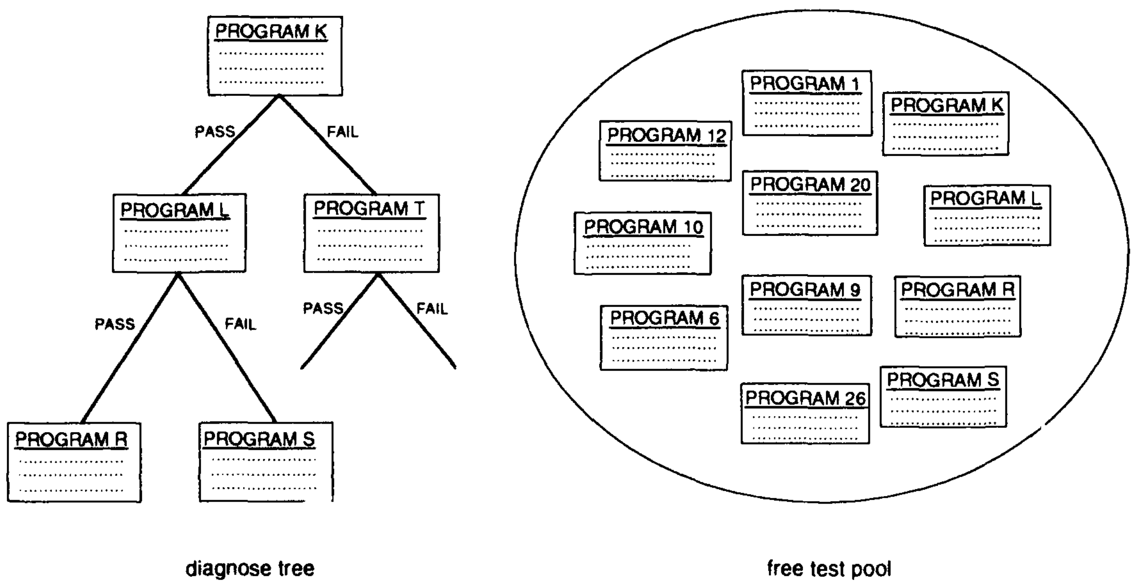

Figure 3-1 Diagnose structures

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The conventional method used to perform a diagnostic routine is to construct a diagnosis tree on which each test result is represented by a node. There are only discrete decision branches, e.g. yes/no, pass/fail, true/false, etc. According to the probability theory, these decisions are 100 % accurate. Consequently, all of the possibilities must be taken into account when constructing the diagnosis tree. Only these predefined decisions produce a diagnostic result.

This diagnostic procedure generally does produce an extremely satisfactory result for non-complex modules with a small number of test points which can be accessed easily. The disadvantage with this method, however, is that subsequent modifications can require considerable time and expense.

Another method of performing a diagnostic routine is to ask after every intermediate test result which test will increase the probability that a hypothetical fault location will be confirmed. This method is based on probability analysis. The advantage thereby is that the rigid test sequences are replaced by a free test pool. The procedure is only generated by a concrete fault. A further advantage of this method is that it can be expanded as required and also takes into consideration any improbable fault types in the test subject. The required programming is performed using an expert system.

As a further strategy, it is necessary to define the size of the individual elements in the test pool. The module structure of the TICAMS test program offers two ways of doing just this. Firstly, a test-pool element can be defined as a test module. Secondly, a test-pool element can be defined as a test sequence. It is not possible to say at the outset which of these methods will be less time consuming. A test sequence is indeed specific but the measurement must be initialized for each sequence. If several test sequences are performed consecutively, the required time may be considerably greater than with one test module, in which a rigid set of test sequences is defined and which consequently can be included in the previous initialization.

A further criterion which must be considered is the point at which the system switches to the diagnosis branch after a fault has been detected. In a diagnosis tree, the system automatically continues in the tree structure after the first fault has been detected. This requires first that all of the previous measurements have also been performed, i.e. the diagnosis procedure can only be conducted from a "complete test program" mode. Secondly, test modules or sequences which have not yet been performed but whose results are required first in the diagnostic tree must be incorporated into the test program several times.

These factors are not required with a free test pool. A diagnosis procedure can be initiated before any test module. Furthermore, each test module/sequence is only required once by the system.

TICAMS transmits each test result to the expert system continuously so that the latter is always informed of the current test status. If a fault occurs, the expert system assumes control over the remaining test procedure.

In order to perform a diagnosis procedure with optimum time requirements for each specimen, the following can be selected via resource files and modified if necessary:

- diagnostic-tree structure
- diagnosis expert system
- test selection via test module
- test selection via test sequence

3.4 Expert Systems

3.4.1 General

Artificial intelligence is an area given to considerable research and development throughout the world. The sub-field of expert systems is thus extremely advanced and has stabilized to such an extent that good software tools are now available for the special applications which are common to electronic diagnostic procedures.

These diagnostic tools, however, have been largely designed to meet only the practical requirements of the user. In general, these tools are simply shells for knowledge-based systems (KBS). The test engineer must first familiarize himself with these shells before they can be applied. Furthermore, in order to create applications in these shells, specific artificial intelligence (AI) languages such as PROLOG, LISP, or SMALLTALK are generally required. These rule-based systems therefore require that each specimen problem be translated into one of these special AI languages. This is generally performed by so-called application engineers who are specialists in the relevant KBS and its AI language. Incorporating specimen information into the KBS, therefore, requires at least one intermediate stage.

In addition, the interfaces of these KBS tools are not designed to meet field or shop requirements and, therefore, must be expanded accordingly - a process which requires considerable time and effort. Furthermore, rule-based systems with an automatic learning mode have not yet been brought on to the market.

3.4.2 Requirements

In view of the reasons listed above, Telefunken Systemtechnik has compiled a list of basic requirements which must be satisfied by an expert system:

- model-based system
- easy to handle by test engineers (without specific knowledge of the internal software structure)
- no need to learn specific AI language
- assistance to implement testability in the UUT
- on-line verification of diagnosis results
- automatic learning

- convenient man/machine interface for operator and developer
- configurable for different diagnostic strategies
- fully-automatic mode

TICAMS provides a standard interface for connecting an expert system so that the latter is freely interchangeable.

3.4.3 AITEST

Taking the basic requirements listed above into consideration, Telefunken Systemtechnik has selected the expert system AITEST and implemented it in TICAMS.

AITEST has been modified in accordance with the basic requirements of Telefunken Systemtechnik and is now available in the revised version.

AITEST functions as a module-based system. The UUT module is entered in the system in the form of an extended block diagram. The system features an internal, universal knowledge base in which the basic principles of electronic diagnosis are stored, i.e.:

- the structure of a block diagram
- the function of electrical switching elements
- basic understanding of electrical measurements.

Figure 3-3 shows the three phases in which a UUT-specific knowledge base can be created, processed and modified.

In this respect, AITEST is equipped with the following features:

During the test-design phase

- test-point optimization from the test point of view
- test documentation based on the Acceptance Test-Procedure level
- test design tools (simulation of test scenarios) to support table-top test program (TP) development
- debugging aids for the Test Programs
- automatic generation of Test Program-control flow

During the test-execution phase (see also Figure 3-2)

- comprehensive hierarchical diagnostic assessment
- cost-effective dynamic test sequencing
- communication with the test system
- test data logging into archive files

During the post-test phase

- data collection from different sites
- automatic learning of diagnostic knowledge
- statistical and data analysis.

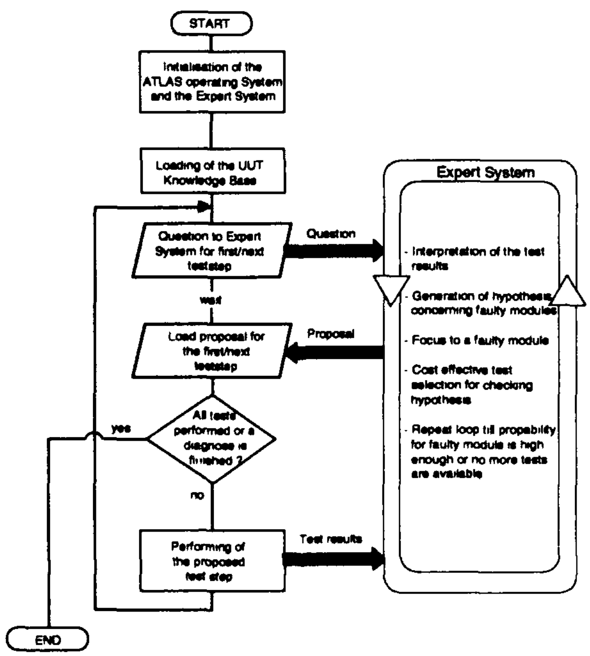

Figure 3-2 Effect of the expert system on the test sequence 20508 011

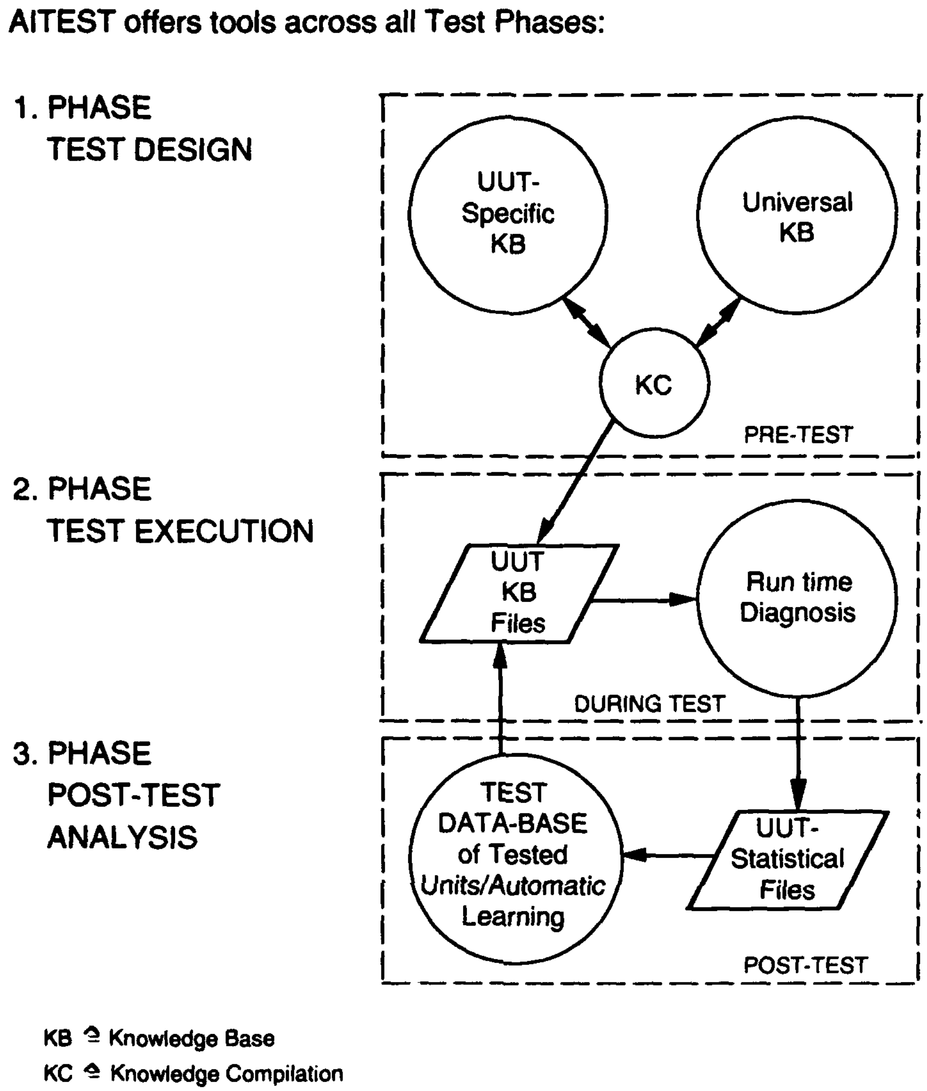

Figure 3-3 AITEST architecture 20508 009

AITEST was implemented in TICAMS based on the afore mentioned features and is available as a diagnostic tool for all test specimens. The post-test features of AITEST are only used at one central location to facilitate central software configuration control over the UUT knowledge bases.

The automatic learning mode is implemented specifically. Each learning procedure is based on statistical calculations which can be used to modify the probability values in the knowledge bases so that more accurate diagnostic results can be obtained. New specimen information or "real-life experience" from the production or application processes can be easily implemented in the system.

Each learning procedure is thus fully reversible. The internal, statistical calculations guarantee a convergence versus stability, even with different learning curves.

3.5 Electronic Documentation

Normally a whole range of technical publications in the form of handbooks or microfiches is available for operating, maintaining, repairing, checking and calibrating the test system as well as for the test specimen itself. Each of these technical publications represents a source of information for the user. Since data processing is nothing but a means of

processing information, it seems logical to store these publications on electronic media, i.e. as electronic documentation. The problem, however, is a matter of user acceptance, as no-one likes to read a text, page for page, from a screen. Diagrams, graphs etc., however, are more acceptable. This is undoubtedly due to the fact that they contain a higher information content on a smaller area. Hence the saying: "a picture paints a thousand words!".

The solution to this problem, therefore, is to convert as much of the text as possible to diagrams, graphs etc.

When implementing the documentation in TICAMS, considerable importance was attached to the fact that specific, electronic documentation for each individual operation should be available to the user, both in its general form (training mode) and as part documentation, as relevant for the various work stages (on-line mode).

3.5.1 Document Types

Depending on the type of technical publication, it can either be displayed directly (1:1) on the screen or must first be converted accordingly.

Conversion, in this sense, means that the publication is not compiled in the conventional manner but is first adapted accordingly.

The following is a list of the different types of technical publication with the corresponding type of display on the screen.

- Configuration lists are generally present in data-bank structure and can thus be easily transferred
- Operating manuals are usually in text form and therefore must be converted
- Maintenance manuals are usually in text and illustrated form; conversion is recommended
- Repair manuals are generally in illustrated form and are therefore ideal for conversion to videos
- Functional descriptions are mostly in text form. Except in an abbreviated form, it is not recommended to supply this information on the screen
- Block diagrams are in illustrated form and therefore can be easily recreated on the screen as brief information
- Schematic diagrams are generally in large format. It is not recommended to recreate these on the relatively small screens.
- Spare parts catalogues, illustrated parts catalogues are present in text and illustrated form. The text is in data-bank structure. The entire representation can be displayed on the screen.

3.5.2 Interface for Documentation Tools

TICAMS provides standard interfaces for the documentation tools. The modular and freely configurable Graphics User Interfaces (see section 3.1) enable new documentation tools to be entered at any time.

At present, the existing TICAMS implementations have interfaces to the following:

- CIROS
- Hyperdoc
- Video Support System

The interfaces are designed in such a way that the documentation can be called via the Graphics User Interface both as general documentation (training mode) as well as specific part documentation for individual procedures.

3.5.2.1 CIROS

The CIROS system facilitates the use of an illustrated parts catalogues, spare parts catalogues as well as a configuration control. Furthermore, access to the warehouse-management and ordering systems can also be implemented via CIROS.

3.5.2.2 Hyperdoc

Hyperdoc facilitates the use of brief descriptions and block diagrams.

3.5.2.3 Video Support System

A whole range of technical publications can be displayed effectively on the screen by means of the video support system Typical application areas include:

- disassembling/reassembling the UUTs
- connecting/disconnecting the UUT to/ from the test system
- manual intervention during the test (e.g. manual measurements, adjustments etc.)
- module-change activities
- calibration activities
- self-test activities
- training activities for handling the test system
- UUT training (function, mechanical layout, maintenance activities etc.)

All of the videos in the video support system are of modular structure. A variety of video sequences are displayed during the test procedure, depending on the skill level of the user. Each video sequence can be accompanied by additional information such as part numbers, order information, notes etc. In addition, any commentaries or sounds can also be included in the videos.

Both video players and optical disks can be used as video systems. The video system is controlled by the computer.

The video support system can be controlled both directly from a test program and from a Graphical User Interface (GUI) as a user aid. To this effect, the video sequences for a respective procedure are selected directly. The user can select any desired video sequence via the general training mode.

Each video sequence can be operated via a GUI of the Video Support System (VSS) or via a remote control unit located directly at the work place for the specimen. A parallel video monitor can be connected to the video support system for this purpose. This is useful with larger test systems where the test specimen is located a few meters away from the standard operator's console.

The video sequence can be operated as on a standard video player by using the GUI or video remote-control unit, i.e. the standard functions such as start, stop, pause, acknowledge, repeat, fast forward etc. can be performed. These functions, however, are only possible within the selected video sequences.

3.6 Evaluating Results

3.6.1 Reports

TICAMS feature two separate report systems. The first is a test-system log book, in which all of the operations can be recorded. These operations refer to the defined activities such as initiating an activity, starting a test program, terminating a test program etc.

The log book can be inspected by a supervisor and can be deleted after backup copies have been made.

TICAMS also features another report system in which the individual test results during the test sequence and the associated diagnostic results are stored. The stored test results can then be printed out in hard copy form or displayed on the screen. The backup/restore functions can be used to store the reports to tape/diskette from which they can be recalled when necessary.

3.6.2 Statistics

The report system for the test results can also be used to compile statistics using the various test results. If necessary, these can also be compiled via a network for several test systems. This enables weak points in the specimens and tester problems to be determined.

3.6.3 Quality-Assurance Systems

A further feature of the TICAMS system is that it can be connected to a quality-assurance system. To this effect, the test and diagnostic results are transmitted to the quality-assurance system. One such tool for this purpose is the FRACAS system. The interface for this system is already implemented in TICAMS. FRACAS (Failure Reporting Analysis Corrective Action System) is used to locate weak points in the specimen and, after successful analysis, implements corrective measures by redesigning the test subject.

Like the interfaces for the electronic documentation systems, the interface for the quality-assurance system is also freely expandable with the result that other quality-assurance systems can be connected to TICAMS.

3.7 Networking

As shown in figure 4-1, all of the systems implemented in TICAMS, such as the electronic documentation tools and all of the external tools such as FRACAS, configuration control and warehouse-management systems can be addressed via a network.

TICAMS functions as standard with a LAN/Ethernet connection, thus providing a wide-ranging network facility. A remote data transfer unit can also be connected for further requirements (see section 5.3).

This feature therefore ensures that new software tools can be connected to TICAMS at any time.

4. STRUCTURE OF TICAMS

TICAMS is designed for implementation in a variety of application areas. In order to meet the latest developments in the area of Integrated Logistic Support, TICAMS has been designed as a fully modular system (see figures 4-1 and 4-2). TICAMS can be modified in accordance with the hardware of the test system. The system, therefore, is largely independent of the test configuration. The range of applications covers both stationary and mobile test equipment in the military and civil fields. This configuration flexibility is due to the modular hardware and the modular software structure of the test equipment.

In order to use the full capability of TICAMS with regard to minimum test, diagnosis and integration time and maximum user support at optimum cost conditions, the application test programs should be designed as modular structures, in as far as this is possible. The test language is not of prime importance. TICAMS is currently being used to generate application test programs in ATLAS - a language which is specially designed for signal simulation, measurement and evaluation.

Additional expansions to TICAMS selected by the user, depend on both the test specimen which is to be supported by TICAMS and on the user environment.

The complexity of the test subject will determine the need for expert systems for diagnostic support, configuration-control modules/tools and with variable specimen configurations, the incorporation of failure analysis systems in the area of quality assurance or direct access facilities to the warehouse management systems.

The required software modules are fully supplied either directly by TICAMS or via a network. In this way, the system can be configured according to the specific requirements.

The user-support system via on-line documentation requires a high degree of adaptability. TICAMS provides interfaces for documentation tools which can be freely defined in the system. The system is easily expanded without requiring modification to existing applications. In this way, existing applications can be expanded subsequently by means of on-line documentation, e.g. by a video support system.

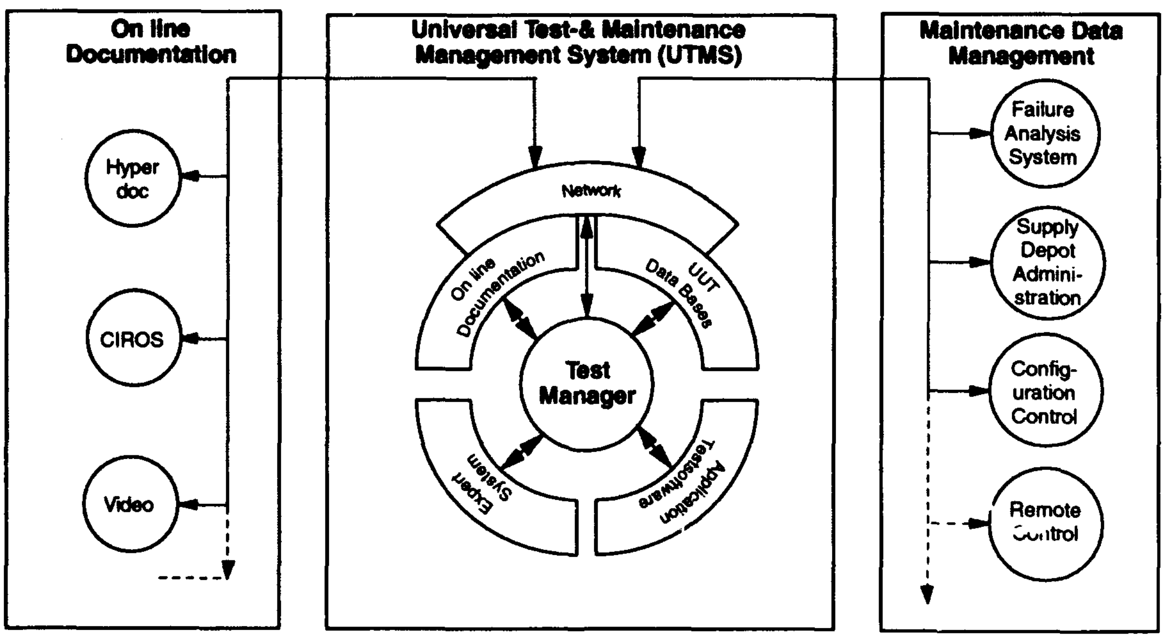

Figure 4-1 Interface structure of TICAMS 20508 014

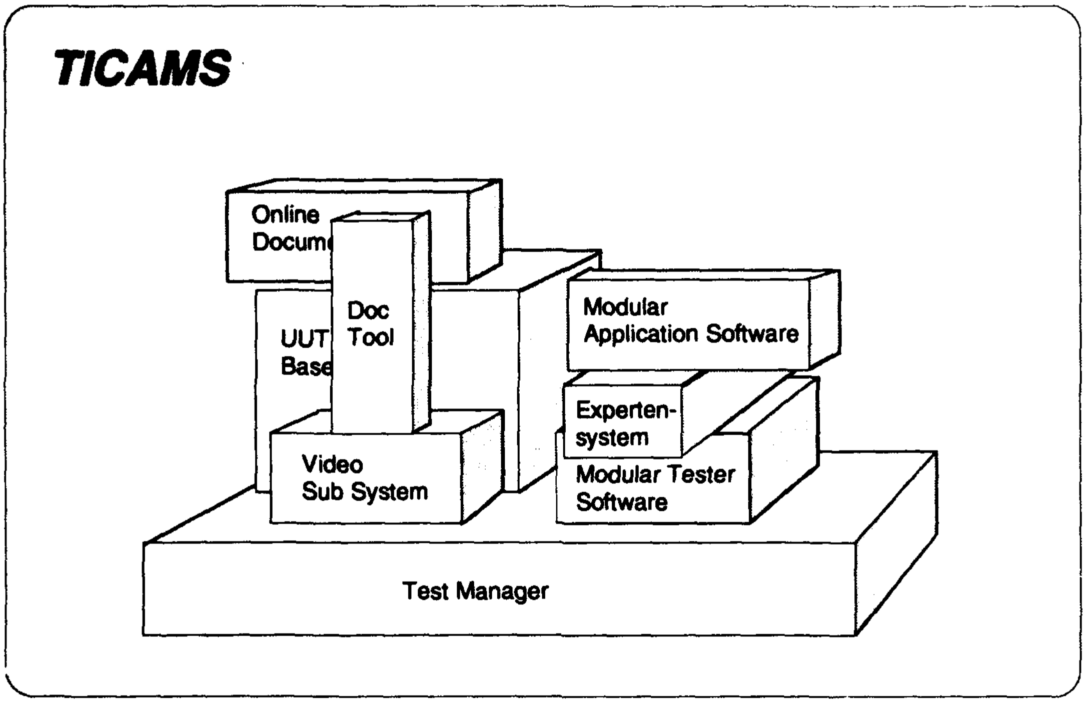

Figure 4-2 Modular structure of TICAMS 20508 006

5. TICAMS IMPLEMENTATIONS

Figure 5-1 shows the planned fields of application for TICAMS. The system is primarily suited for implementation in areas where complex electronics and RF signal processing require the use of modern test equipment with the associated comprehensive test documents, test subject descriptions, training documents and efficient network structures.

These applications cover the entire spectrum of military test applications - both as stationary and mobile test stations, in the field of radar, electronic warfare and avionics equipment and for digital and video applications as well as microwave applications.

Implementation in civil applications is also planned for production processes in the avionics, automobile and general RF-equipment industries as well as in the field of quality assurance.

5.1 Tornado Self Protection Jammer

TICAMS is currently being used by the German Air Force for its Tornado Self Protection Jammer. An expert system is first being implemented in the Aerospace Ground Equipment (AGE) for diagnosis operations.

In addition, the video-supported user guidance system and the full electronic documentation system are also being used. CIROS, Hyperdoc and VSS have been implemented as documentation tools. The CIROS system supplies the configuration control, replacement-part catalogue and the illustrated parts catalogue. Hyperdoc is being used for the functional descriptions and VSS for all of the videos. Figure 5-2 shows how TICAMS has been implemented in the Tornado Self Protection Jammer. The station covers the signal and measurement range from digital to microwave levels.

5.2 Eurofighter ECR 90 Radar

Further components for TICAMS have been implemented within the framework of the development contract for the Eurofighter ECR 90 Radar. These are, in particular, the connection to the FRACAS quality-assurance system (Failure Report Analysis Corrective Action System) and the expansion of the report systems for performing statistical evaluations over several specimens and test systems. These expansions are mostly due to the ILS requirements as defined for the Eurofighter ECR 90 Radar.

5.3 Growth Potential

The implementation of further TICAMS components is planned for the future.

Among other developments, TICAMS is to be connected to a remote data transfer (RDT) system so that

- the self-learn capability of the expert system can handle overlapping tests more rapidly
- external configuration control and software monitoring and modification can be performed.

The test and diagnostic results are to be transferred via RDT to a central location for the self-learning facility of the expert system. From this location, the knowledge bases for the test specimens will be maintained via the self-learning mode and the new knowledge bases will be loaded into the test systems via RDT.

The external configuration control and software maintenance and modification will be performed via a shared X-mode. This mode enables a central location to participate in the execution of the application parallel to the test operator, thereby increasing the effectiveness and speed with which software problems are located. Furthermore, software updates can thus be copied to the system and a configuration check performed simultaneously.

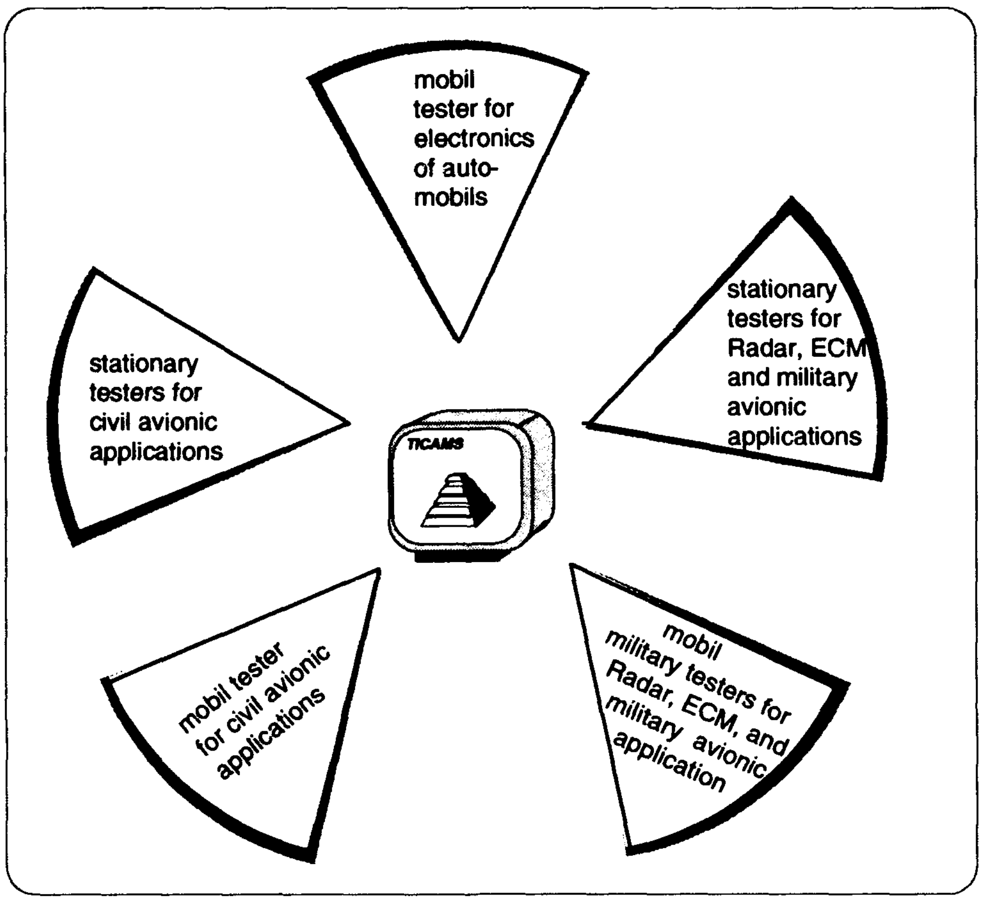

Figure 5-1 Application areas for TICAMS 20508 008

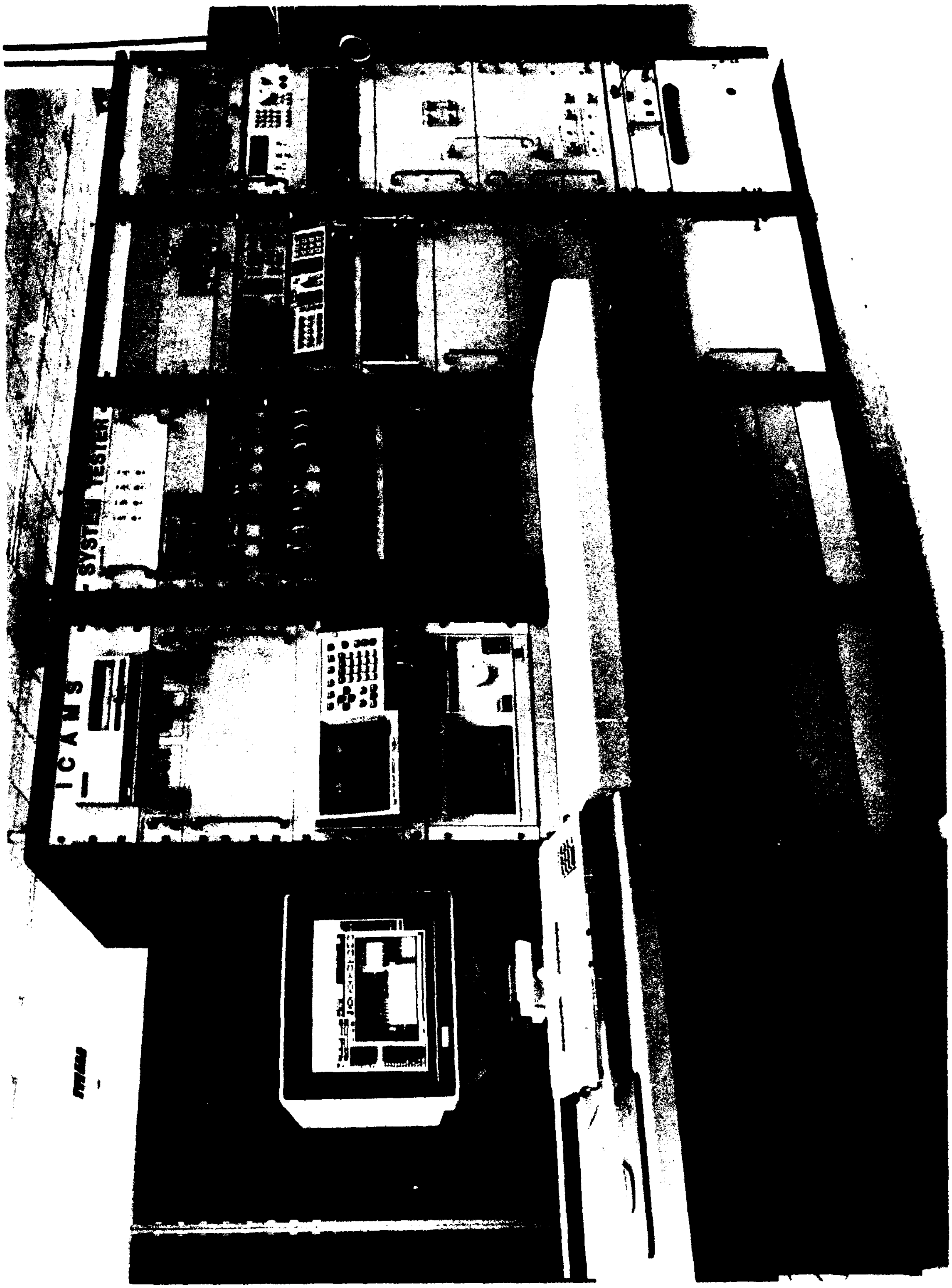

Figure 5-2 Realisation of TICAMS as TSPJ Tester

6. CONCLUSION

In the future, the experience gained regarding life cycle cost relations in modern, complex systems (especially in the field of avionics) with their exceptionally unfavourable cost-intensive conditions during their utilization phase will oblige all equipment - and system manufacture, especially under the aspects of a policy of a lack of funds, to promote the transfer of costs from the recurring area into the non-recurring area and thus to invest funds in an earlier phase.

This policy will cause a slight increase in development costs but, at the same time, will reduce the costs in the utilization phase considerably.

TICAMS will be an excellent means of influencing and reducing the recurring cost factor.

The dramatic increase in life cycle costs in the production and series phases has led to the need for a system which reduces the costs resulting from the actual tests, the required repair work and the associated documentation and training to a minimum.

This system must resolve the problems of the individual activities in these phases for each phase and activity. This requires both an incorporation in the production system of the manufacturer and in the complete application system of the user.

This incorporation increases the demands made on such a system by the user with the result that extensive, cost-intensive training is required. TICAMS places considerable emphasis on this aspect, so as to minimize the costs involved.

The support provided by TICAMS ranges from the use of highly-developed diagnostic-support systems and developed user guidance as well as the use of electronic documentation to networking with other systems.

> TICAMS is our solution in the battle against rising life cycle costs.

> TICAMS enables simple handling of highly complex technology.

Maintenance for us not only obliges the ILS team and especially the maintenance engineer to prove that they are necessary; when considering the various groups of interests with their motivation on both the user and the manufacturer side, maintenance is also a task which today concerns everyone involved in system development and utilization for different motivations either

> in the technical, in the tactical or the economic field.

This discipline starts in the study and concept phase of a product and extends to the production phase via the definition and development phases and finally ends when the series phase is completed.

This shows that the test systems which are necessary for a type of equipment must follow the same rules and support the system over all of the phases. Only such a system can support the equipment in accordance with the ILS requirements.

TICAMS represents an effective means of gaining control over life cycle costs.

DEVELOPING VIRTUAL COCKPITS

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SUMMARY

The motivation for development of virtual crew system technologies stems from the growing complexity of cockpit interfaces and the realization that humans are spatial beings who are much better equipped to process and control information if it bears a spatial and temporal relationship to the way the real world exists at the moment. The virtual cockpit will provide three-dimensional (3-D) spherical awareness, intuitive control interfaces, and automated assistance to the pilot. Three-dimensional visual and auditory information will be presented via the pilot's helmet, while tactile information may be presented through micro-stimulators within the pilot's glove, which are activated as a function of hand and/or finger position within the cockpit. The intent is to build a virtual cockpit that creates a representation of the look and feel of the real world, to the extent that the interaction with the display and control of information is as natural as possible. The notion of a virtual cockpit has been popularized in the "Super Cockpit" concept. The Super Cockpit concept demands a functional integration of a broad range of advanced control, display and avionic technologies. The successful marriage of the individual capabilities that each of these technologies represent demands an understanding and appreciation of the requirements for sensing, processing and displaying information to provide the pilot the advantage of 3-D spatial/situational awareness throughout the mission. This paper addresses the multifaceted development issues associated with realization of the virtual cockpit.

1. INTRODUCTION

The guiding principle supporting development and integration of virtual cockpit technologies is that the best possible control/display environment for the pilot would be one that duplicates the essential organization and content of the real world as simply as possible, while providing natural and intuitive control interfaces with the aircraft and objects in the outside world. In its ultimate form, the virtual cockpit would provide a computer generated world (see Figure 1) in which all information is displayed in 3-D visual, auditory and tactile space, while communicating an overall awareness of the weapon system state, relative to everything in the environment. Based on head position and/or eye line-of-sight, the pilot would see a wide field-of-view (FOV) binocular display providing an electronic representation of the terrain. Way points and targets that may have been designated by that pilot or a member of a previous flight are overlaid on the terrain. Also displayed are the position and state of on-board weapons, ground and airborne threats and their status (e.g., the lethality envelope for surface-to-air missile sites may be shown in red), a safe highway in the sky, and heading information on the horizon. System status information may be windowed in and windowed out as needed. The optical flow of objects in the visual periphery gives natural cues as to altitude, attitude and airspeed, without resorting to the conventional display of flight symbology. An outside-in display showing a God's-eye-view of the aircraft and the surrounding scene is selectable to provide enhanced situational awareness, allowing hand and voice interaction with the displayed elements. A vibro-tactile stimulator in the pilot's glove (see Figure 2) provides tactile feedback when the pilot interacts with objects in the virtual visual environment. Three-dimensional sound is provided through the pilot's earphones, allowing localization of the relative position of airborne and ground threat systems, launched missiles, wingmen, and other sensed objects (see Figure 3). Through an on-board processor, displayed information is specially conditioned, based on the mission as planned, the events that have just preceded that point in the mission, an estimate of the pilot's intentions, the sensed array of objects within and beyond visual range, and the state of the pilot, both in terms of

physiological and workload capabilities. The consciousness state of the pilot is monitored by sensors in the helmet that monitor such parameters as blood flow to the brain, eyelid behavior and heart rate. If the measures indicate the pilot is unconscious, and if the flight parameters indicate that a crash is imminent, then, based on prior pilot consent, the aircraft will be automatically recovered. Rapid reconfiguration of cockpit controls and displays is also under the pilot's command. Display/control configurations are specified in the Data Transfer Module (DTM) that the pilot loads into the system prior to start-up. The DTM also contains the pilot's voice print for voice control of selected system functions (previously collected under various g-loadings and stress states), along with the pilot's head-related transfer function (for customizing the 3-D sound to the physical characteristics of that pilot), premission system setup tailored to that mission, as well as to the preferences and experience base of that pilot. Automated assistance to the pilot, in the form of a "Pilot's Associate" will behave much as a long-trusted backseater, whose actions the pilot can understand and anticipate, and whose vast array of experience and expertise can be immediately brought to bear during periods of high pilot workload or physiological stress.

The virtual cockpit can provide its own embedded training. While on the ground, the pilot can rehearse the entire mission. Once the DTM is loaded, the system may be set to the rehearsal mode, and thereafter behaves just as it would under actual flight conditions. The pilot may elect to encounter any number of ground and/or airborne threats at random but logical times during the rehearsal.

After the actual flight, the virtual cockpit becomes a boon to the maintenance technician as well. Conventional aircraft do not provide the opportunity to review a reported malfunction exactly the way it appeared to the pilot. Instead, the maintenance technician must try to duplicate the failure on the ground, an environment vastly different from the airborne one in which it occurred. This often leads to reports of "cannot duplicate", resulting, at a minimum, in much wasted troubleshooting time, in addition to frustration by both the technician and the pilot. Using the virtual cockpit, the technician is able to review the recorded events exactly as they were displayed to the pilot. The technician becomes an astute observer, since he or she knows exactly what to look for and when to look for it.

The virtual cockpit may also provide defense against laser threats, since all the information needed to fly and fight could be displayed on the pilot's helmet visor, without reference to the outside world. Application of this same technology to the control of unmanned air vehicles (UAVs) is obvious. The same flying skills the pilot used in the aircraft could be employed to fly an unmanned vehicle from a control facility, remote from the air vehicle itself.

The genesis of the display and control portions of the virtual cockpit lies in the development of advanced helmet-mounted display and sight (HMD/S) systems that are now gaining operational exposure. Figure 4 shows a conceptual representation of a medium field-of-view, binocular HMD. The U.S. Army is producing the AH-64 (Apache) helicopter with the IHADSS (Integrated Helmet and Display Sight System). The IHADSS is a monocular system having a single cathode ray tube (CRT) attached at the side of the helmet and projecting a FLIR (forward looking infrared) image onto a combiner glass, separate from the visor. The Armstrong Laboratory is supporting the advanced development of HMDs that allow the pilot to see an image intensified scene (using third-generation image intensifiers) or a raster scene (as from a FLIR sensor), with or without flight symbology, and viewed so as to be superimposed on the outside world. This provides for fail safe operation, since the real world always remains accessible. These helmets are being evaluated in a comprehensive ground and flight test program to demonstrate ejection compatibility, comfort and safety, optical and acoustic performance, and operational utility. Figures 5 and 6 show front and side views, respectively, of an HMD configuration developed by the Armstrong Laboratory and known as TOPHAT. This design features a frangible combiner that separates from the rest of the helmet, should the pilot eject from the aircraft.

2. AVIONIC DATA SOURCE REQUIREMENTS

It cannot be stated too strongly that the fundamental reason for providing information to the pilot is to convey an accurate impression of the present situation, relative to the objectives of the mission. The pilot needs to acquire and maintain spatial situational awareness. This requires that he knows where he is relative to the terrain, waypoints, landmarks, ground and airborne threats, his wingmen, ground friendly forces, and the target(s). He must use this information to assess what should be done during the next few moments and how that compares with the perspective he has on the mission as planned, or as recently reformulated within his mind. Since the pilot is totally dependent on the viability of his aircraft, it is crucial that aircraft and weapon status information be provided, but only when needed to convey information important at the

moment, or to construct strategies to overcome new contingencies.

Many of the functional assists to the pilot in the areas of mission planning, tactics development, system status monitoring, situation assessment and design of the pilot-vehicle interface (especially for head-down displays) are being addressed within the Pilot's Associate program being managed by the Wright Laboratory at Wright-Patterson Air Force Base, Ohio. It is not within the scope of this paper to address the capabilities being developed under that effort, though they are relevant. A detailed discussion of the Pilot's Associate program may be found in the paper by Banks and Lizza (Ref 1). See the paper by Hopper (Ref 2, immediately following this report) for a description of technologies supporting development of large area head-down displays.

The virtual cockpit will depend on inputs from a broad range of avionic sensors for the collection, processing and display of information in real time. For purposes of discussion here, real time will be considered to be within one frame-period of when the data was collected. The most stringent requirement has to do with above ground level (AGL) information, from whatever means is available, to assure the pilot maintains safe vertical ground clearance. Determination of horizontal situation may be provided by an Inertial Reference System (IRS), the Global Positioning System (GPS), or an airborne surveillance capability. As discussed below, this positional information may be fused with either sensed data (as from a FLIR, Low Light Level TV, or radar) or an on board terrain database to provide the pilot scene context information on the HMD.

3. SENSOR INTEGRATION

Information displayed in the virtual cockpit must represent an integration of on board stored digital terrain elevation and feature data, with sensed, but processed, all-aspect air-to-air, together with air-to-ground, radar inputs. Supporting and/or verification information may be provided by a broad range of avionic systems, including threat receivers, radar altimeter, IRS, GPS, Infrared Search and Track (IRST), Identification, Friend, Foe or Neutral (IFFN), Joint Tactical Information Distribution System (JTIDS), Airborne Warning and Control (AWACS) or other sources. Stanley (Ref 3) discusses challenges and issues in achieving an integrated sensor suite. Today, issues of cost, volume and weight represent primary technological hurdles facing developers of advanced avionic systems. As advances in sensor technologies are made, the impact of software capable of controlling and managing a federated sensor suite supporting the virtual cockpit in real time will become even more critical. The software must be able to allocate sensor resources based on random mission events, known events, and at times, insufficient information. This dynamic reconfiguration must be capable of fusing on board and off board sensor and database assets and be supported by sufficient intelligence (perhaps via Pilot's Associate technology) to be able to display a coherent synthesized graphic output to the pilot.

4. DATA PROCESSING AND THROUGHPUT REQUIREMENTS

Thus, one of the most difficult challenges to be dealt with in the development of the virtual cockpit has to do with data fusion across the suite of sensors, stored terrain and intelligence information, and complementary data received in-flight. There are several aspects of the data fusion issue that warrant discussion here. The first consideration is one of spatial correlation of data across the several spectral sources. The correlational process must remain robust under variations of spectral power (since different parts of the spectrum are being sensed by different imaging sensors), and spatial distortion due to atmospheric and/or optical attenuation across sensors. Any display of fused raw imagery (e.g., a integration of FLIR and Low Light Level TV) must be sufficiently registered spatially so that the combined images overlaid throughout the sensed area make sense visually to the pilot (there will be more discussion of this in Section 5., below). If the sensed data is processed and target recognition, or other algorithms, are applied to translate from the sensor format to an encoded graphical representation of the scene, the correlation problem may become even more critical due to the inability of the processing algorithms to recognize confusions that the pilot may be able to resolve. Similarly, if an automatic target recognizer (ATR) produces false alarms above some rate the pilot finds acceptable, its output will be either disregarded, or considered to add unreasonable workload and be turned off by the pilot. This is a critical area for research, since performance of the ATR is likely to have its greatest impact during the very most heavily loaded segments of the mission.

Once the information is extracted from sensors and/or a stored database, the temporal capabilities of the data processing routines as well as the graphics generator used to draw the scene on the image source within the HMD become the critical limiting factors driving the utility of the information to the pilot. Whatever processing delays are present will be added to head position sensing (i.e., helmet mounted sight) system delays. See Kocian (Ref 4)

for a discussion of "Advanced Helmet Mounted Display Electronics" and "Magnetic Helmet Mounted Sight" design and performance, reflecting today's technology available for supporting HMD engineering and human factors research.

A major goal of the software development efforts supporting the virtual cockpit technologies must be to place tight restrictions on allowable throughput delays. Successful development will demand the cooperative efforts of software and hardware designers alike, since the basic architecture of the avionics system (e.g., distributed versus federated) will place physical boundaries on data processing and distribution speeds. Another important limitation on the temporal capabilities of the system is imposed by the nature of the databus. The virtual cockpit will require several fiber optic data links among the various sensors, processors and display units.

5. HUMAN SENSORY, PERCEPTUAL AND COGNITIVE REQUIREMENTS

The primary purpose of the virtual cockpit is to convey situational awareness to the pilot. The preceding sections of this paper have emphasized that several attributes of the hardware and software that drive sensor, processing and display capabilities also drive the pilot's ability to formulate an accurate impression of the situation. There are numerous human factors issues that must be addressed and resolved to assure that the pilot's requirements from the sensory (i.e., psychophysical), perceptual and cognitive, standpoints are satisfied. Furness (Ref 5) discusses many of these issues in the context of being challenges to the human factors research community. Several of the issues raised by Furness are also challenges to the avionics development community and have their counterparts in terms of the hardware and software performance driving the virtual cockpit. A fundamental question has to do with how large the field-of-view (FOV) must be to provide the pilot with "adequate" situation awareness. Aside from the obvious issue of what is meant by "adequate", the answer to this drives the sensor array size, resolution of the resulting display, and processing speed requirements of the display processor. If the scene is being generated by a graphics processor, similar resolution and processing speed requirements are levied. Additionally, when the pilot moves his head and/or eyes, the scene must follow correspondingly so as not to produce annoying or disorienting effects. The display and graphics processors must be able to maintain temporal coherence with the helmet-mounted sight (head and/or eye position) sensing system. Related to the issue of resolution is that of registration accuracy. If the computer generated scene is to be projected onto the real, and/or the sensor generated scene, all scene elements must be registered properly. Similarly, when symbolic information is overlaid on the displayed scene, its position and psychophysical attributes must be carefully designed to assure it is where and what it should be to best convey its meaning to the pilot. In addition to conventional human factors considerations of symbol meaning and legibility will be problems of obscuration and integration of symbology with other elements in the scene. Ideally, the luminance and chromatic contrast of the symbology would be manipulated by the graphics processor to maintain symbol visibility, relative to the background. These issues, together with a great many others dealing with the organization of information in the virtual cockpit and its meaning to that individual pilot can be expected to drive the cognitive utility of the displayed visual environment.

The 3-D auditory information will have similar, though less stringent, requirements for resolution and registration with both the real world and the visual portion of the virtual cockpit. One reason for this is the inherently poorer resolution capabilities of the auditory localization system of the human (i.e., we can localize the direction of sounds to within approximately 5 to 8 degrees, depending on their relative location), as opposed to the visual system (i.e., the ability to resolve two bars separated by 1 minute of arc corresponds to a "normal" visual acuity under nominal viewing conditions). Another reason is that the auditory information may be used primarily to produce an orienting response from the pilot, to direct his attention to the GENERAL area of an object being displayed visually.

The resolution and registration of tactile information (if provided) will be dependent on the position sensing system being used on the pilot's hand, together with the resolution of the tactile micro-stimulators in the pilot's glove, and the registration of that information with the visual virtual environment. The development of micro-stimulators can be expected to represent a substantial challenge to that community.

6. SYSTEM INTEGRATION REQUIREMENTS

Although the integration of the avionic suite supporting the virtual cockpit has been briefly discussed in the sections above, an in-depth treatment of system integration requirements is beyond the scope of this paper. However, there are some cockpit technology integration issues that must be addressed in the process of developing the fully functional virtual cockpit. During the next few decades, and prior to having a full color, wide FOV

virtual cockpit capability, there is a requirement to make the virtual cockpit visual display compatible with other visual displays. A central concern will be the mutual utility of head-down, head-up and helmet-mounted displays, and how information on one display medium can be made to be compatible with (or not disruptive to) information on another. This will require the integration of head/eye position data with display processing so that some or all of the information may be blanked on one display or the other, depending on what information the pilot is looking at, the mission segment, or the task being performed at the moment.

As new avionic capabilities become operationally viable, their impact on the spatial and temporal information processing requirements of the pilot must be paramount considerations in how they are integrated into the rest of the avionic architecture. Integrated properly, the virtual cockpit and supporting avionic technologies promise immense leaps in pilot, system and mission capabilities to fly, fight and survive throughout all flight environments.

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Figure 1. Artist's Rendition of a Virtual Cockpit

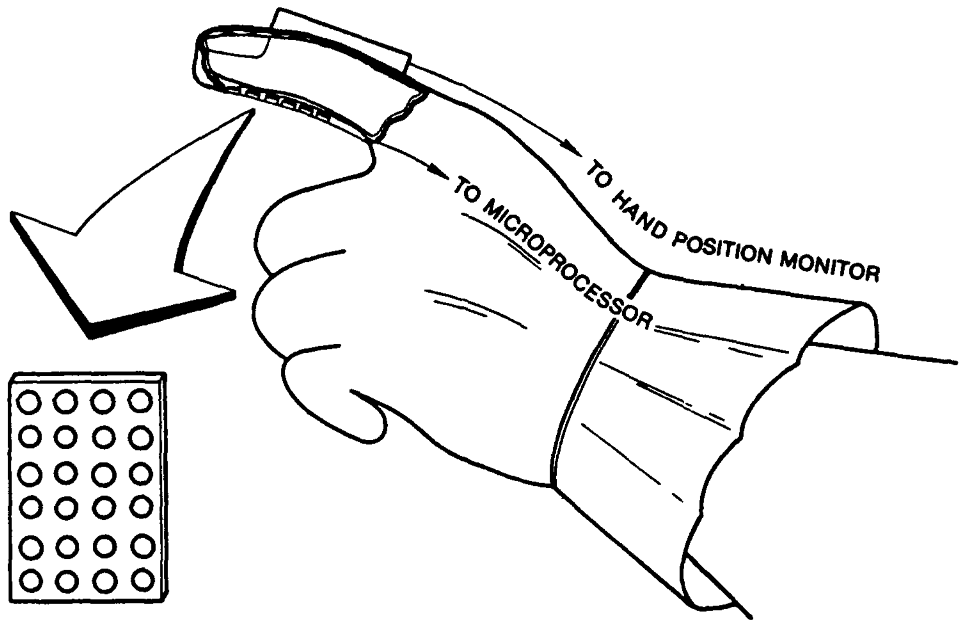

Figure 2. Vibro-Tactile Stimulator and Finger Position Sensor in Pilot's Glove

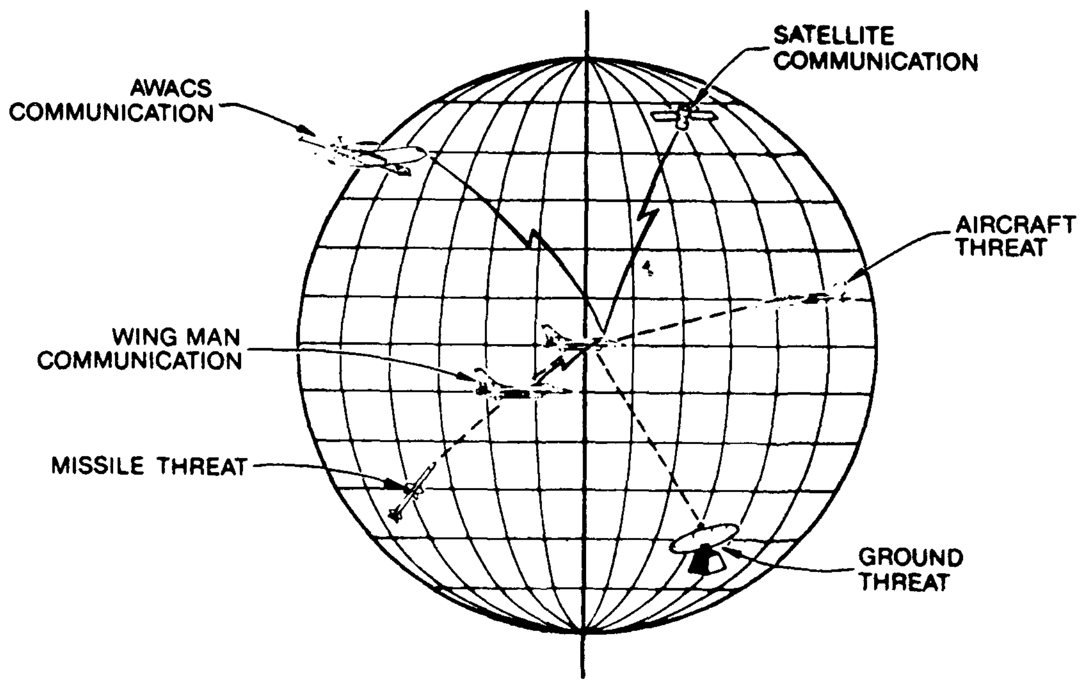

Figure 3. Three-Dimensional Audio World

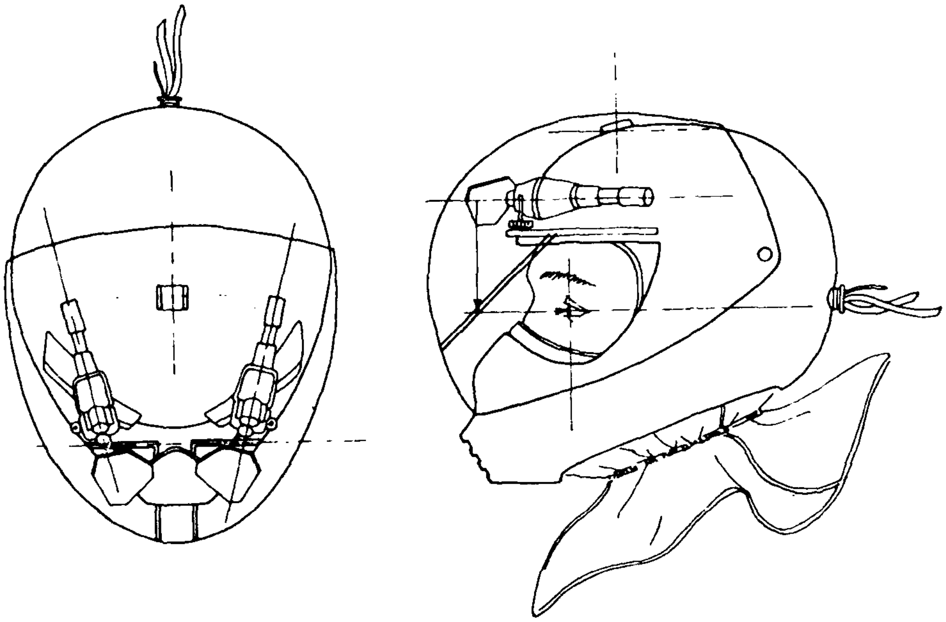

Figure 4. Conceptual Representation of a Medium Field-of-View Helmet Mounted Display

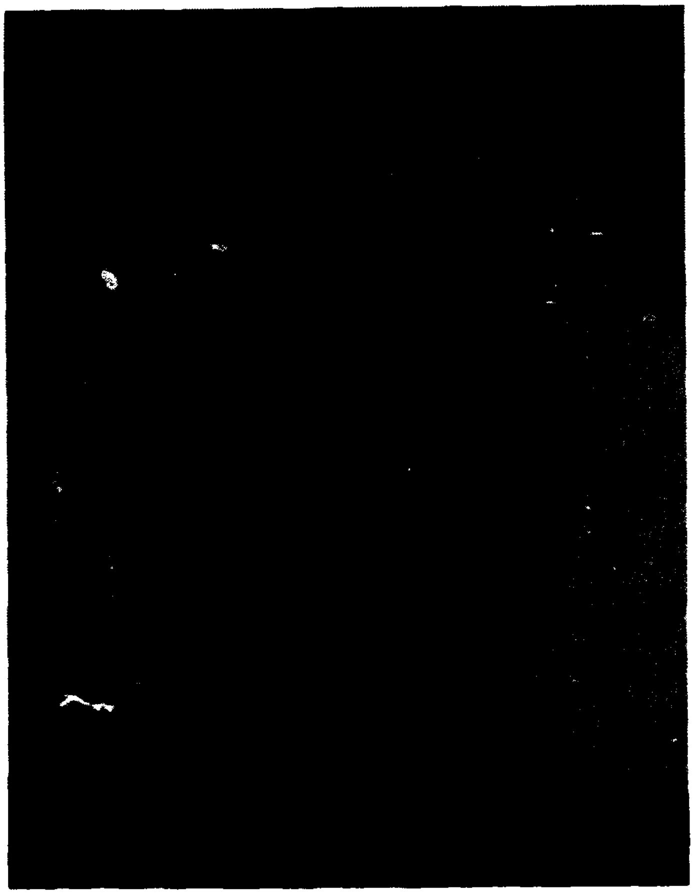

Figure 5. Front View of TOPHAT Helmet Mounted Display

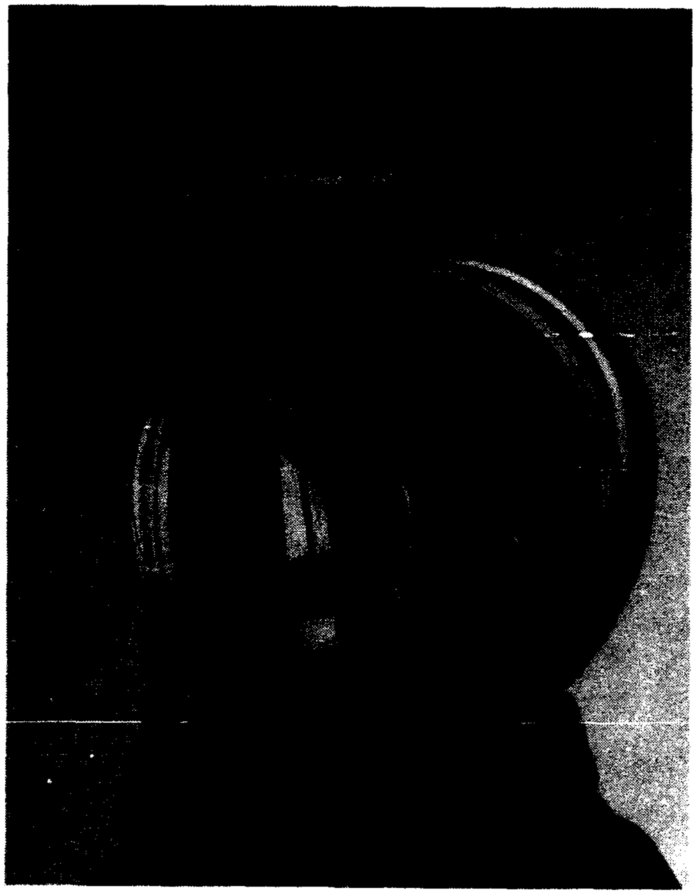

Figure 6. Side View of TOPHAT Helmet Mounted Display

Discussion

QUESTION S. FRANCALANCI

Will the development of a virtual cockpit include substitution of Head-Up display by Helmet-Mounted display?

REPLY

Yes, but not immediately due to some technical (weapon-aiming related) problems. The future cockpit will extend the display area into the area currently used by HUD optics and electronics.

Panoramic Cockpit Displays*

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1. SUMMARY
The great challenge of today's cockpit designers is to provide the 21st century pilot the necessary situation awareness to be effective in combat. This situation awareness is difficult to achieve because a pilot has to look at numerous dials and indicators, multiple small displays with different range scales and ownship locations, and distorted radar images. Today the pilot must fuse all information and be able to make immediate critical decisions in a combat environment. Part of the solution to this information overload problem is a panoramic agile-window display. The advantages of a large area display system were recently demonstrated in the Panoramic Cockpit Control and Display System research program. The principal objective result was a 45% increase in pilot combat effectiveness.

The key to the implementation of the panoramic cockpit concept is a large area display together with a helmet-mounted equivalent of the present day head-up display. The large area head down system uses direct view or projected view to create an aggregate display area of 650-2000 cm^2. The status of cockpit displays is reviewed with an emphasis on hardware. Several technologies are being developed simultaneously and are analyzed here against requirements of our cockpit visions for new systems such as the F-22 and RAH-66, retrofit programs like the C-130/C-141, and advanced fighter and transport concepts.

LIST OF SYMBOLS

AM	active matrix (T,M,P,R) addressing of LC,EL,DM,MP
AMLCD	active matrix (T,M,P) LCD
AMELD	active matrix (T) ELD
AMDMD	active matrix (R) DMD display
AMMPD	active matrix (R) MPD
ANVIS	aviator's night vision imaging system
AOM	acousto-optic modulator
a-Si	amorphous silicon
ASIC	application specific integrated circuit
ATF	advanced tactical fighter (F-22)
AWACS	airborne warning and control system
BVR	beyond visual range
cd	candela (unit of luminous intensity)
CDG	cockpit display generator
CGH	computer generated hologram
CHDD	color head down display
CMD	cockpit mounted display
CRT	cathode ray tube
CVC	combat vehicle crew
DMD	deformable mirror device
EBS	e-beam pumped semiconductor (laser array)
ELD	electroluminescent display
EMD	engineering & manufacturing development
F-22	air superiority fighter
FCRT	flat CRT
footcandle,fc	lm ft^{-2} (10.7639 lx)
footlambert,fL	$(pi)^{-1}$ cd ft^{-2} (3.42626 cd m^{-2})
FLIR	forward looking infrared
FOR	field of regard
FOV	field of view
FPCD	flat panel cockpit display (LED,AMLCD,etc.)
GPS	global positioning system
HDD	head down display
HMD	helmet mounted display/sight
HMS	helmet mounted sight
HUD	head up display/sight
IFOR	instantaneous FOR
IFOV	instantaneous FOV
ILO	inside looking out

* Published in "Advanced Aircraft Interfaces: The Machine Side of the Man-Machine Interface", AGARD CP-521, 1992, Paper 9. Conference Proceedings of the 63rd Avionics Panel Meeting/Symposium held in Madrid, Spain, 18-22 May 1992. Published by the NATO Advisory Group for Aerospace Research and Development (AGARD) Avionics Panel (AVP).

JCO	Joint Cockpit Office of AL,WL
JTIDS	joint tactical information distribution system
lambert,L	lm cm^{-2}, $(pi)^{-1}$ cd cm^{-2} [obsolete]
LC	liquid crystal
LCD	liquid crystal display
LED	light emitting diode (display)
LH	RAH-66
lumen, lm	cd sr (unit of luminous flux, F)
lux, lx	lm m^{-2} (unit of illuminance, E)
M	magnetic (NiFe)
MAWDS	multifunctional agile window display system
MFD	multifunction display
MPD	microtip-field-emission-plate phosphor display
MTAC	mission/task adaptive cockpit
NVG	night vision goggle
OLI	outside looking in
P	plasma
p-Si	polycrystalline silicon
PALC	plasma addressed LCD
PCCADS	panoramic cockpit control and display system
PC	panoramic cockpit
PCD	panoramic cockpit display
PDLC	polymer dispersed liquid crystal
HIFOV	high-resolution IFOV
pixel	picture element (2-D display)
R	random access memory (RAM)
RAH-66	reconnaissance/attack light helicopter, "Commanche"
RAMTIP	reliability and maintainability technology insertion program
RGB	red-green-blue
SC	super cockpit
SFD	small format display
SIPE	soldier's integrated protective ensemble
SLM	spatial light modulator
smafhired	small format high resolution display
SOF	special operational forces
SSLD	solid state laser display
sygvrew	synthetically generated view of the real world
T	transistor
TFT	thin film transistor (in Si, CdSe)
TN	twisted neumatic (LC)
VDMS	visual display modelling system
VFR	visual flight rules
voxel	volume element (3-D display)
WL	Wright Laboratory
YGB	yellow-green-blue
XGA	extented graphics array
x-Si	single crystal silicon

2. INTRODUCTION

This paper addresses hardware developments needed to create panoramic cockpit display systems.

2.1 Threat

Present day combat pilots suffer from information overload. The result is decrease or loss of situational awareness (SA) at times when it is most important. Beyond visual range (BVR) objects are also difficult to envision and fit into a total picture. These threats, together with night, in-weather, low-level flight conditions and the laser threat, may require panoramic displays in 21st century cockpits. The future military pilot might then have to fly some mission segments--notably ingress, attack, and egress--without any benefit whatsoever of looking out of the cockpit. The direct world view now acquired by the pilot's unaided eyes might be denied even during VFR flight conditions. Fortunately, there is an opportunity, technologically speaking, to provide a degree of information that is not only sufficient, but which may significantly surpass in many regards that currently available through the canopy on a clear weather day. The canopy would be closed by curtains or by an electrically controlled opaquing layer. Then an artificial world view, called virtual reality by some, would be created. The control and display system might logically evolve as an extension of present day night/in-weather instrumented flight systems. Eventually, a large area display suite may become necessary to survival, let alone mission success. Such a system might be a 2000 cm^2 (300 in^2) head-down color multi-function, multi-window display coupled with a head-mounted system and would have to operate with a clear as well as an opaqued canopy.

2.2 PCCADS

2.2.1 *Results*

A program of studies conducted by this office has demonstrated an effective way to deal with the threat just described. The approach in this program, entitled "Panoramic Cockpit Control and Display System (PCCADS)," is to provide the pilot with large area displays and a helmet-mounted off-axis target-acquisition weapon-targeting system. There were two projects, one focused near term, the other, far term.[1]

The PCCADS 2000 cockpit was designed to be realizable with 1995 technology and featured a 25 cm (10 in.) square tactical situation display and two 15 cm (6 in.) square secondary multifunction displays on either side.[2] All displays were full color capable with a total area of 1110 cm^2 (172 in^2). The test mission was for an F-15E. A 28% increase in exchange ratio was achieved versus the standard F-15E cockpit. Coupling this large display with a helmet mounted display (HMD) for off

axis target acquisition resulted in a 45% increase. The PCCADS 2000 concept is illustrated in Figure 1. The F-15E displays are depicted in Figure 2 for comparison to the PCCADS 2000 displays, shown in Figure 3.

The PCCADS 2001 cockpit is a variation of the PCCADS 2000 cockpit. PCCADS 2001 features two 25 cm and one 10 cm square, color displays providing a total area of about 1350 cm^2 (210 in^2). Each large MFD can contain four scalable windows. The two MFDs are side by side and can be driven together as one large albeit segmented 55 x 25 cm display array with a 5 cm wide pair of bezel button bars bisecting it.

The PCCADS cockpit was designed to be realizable with beyond 2000 technology and featured a 2000 cm^2 (300 in^2) display. This research demonstrated the payoff in increased situational awareness from integrating all information and displaying it to the pilot on one large display format, with secondary information displayed as needed in windows. This effort actually preceded the PCCADS 2000 effort, which was to show how much of PCCADS could be realized with today's technology. The PCCADS 2000 cm^2 test cockpit for improved man-machine interface is illustrated in Fig. 4.

2.2.2 *Implementation*

The key to the implementation of the panoramic cockpit concept is a large area Head Down Display (HDD)[3] together with a helmet-mounted display and sight having the capacity, initially, of the present day head-up display (HUD) augmented with off-axis capability. There are two complementary approaches: outside-looking-in (OLI) and inside-looking-out (ILO). In the OLI approach, the viewer perceives himself to be located outside looking in on the world presented on the display. In the ILO approach, the viewer perceives himself to be located inside the displayed world looking out at it; a large, 120 x 60°, field of view is required for one to "think" one is actually immersed in the world presented on the display(s). The ILO approach is achieved today via the tranparent canopy: the pilot is centered in a real world with all display elements coming from real world phenomena. Cockpit mounted display (CMD) technology, represented by today's HDDs, represents the OLI approach. Significant development is required for the CMD technology to be used to implement either the large area OLI or, eventually, the ILO approach. The head-mounted version of the either the OLI or the ILO approach requires a much more complicated HMD than one which merely transfers sighting or HUD functions to the helmet: an artificially generated view of the real world is created and presented on what we here term a "small format high resolution display" (smafhired). Research on helmet-mounted virtual cockpits for 2020 is described in the immediately preceding paper by Martin.[4] Research on smafhireds is included here.

The OLI approach to the large area display system uses direct view or projected view to create a display area of some 625-2000 cm^2. An active matrix liquid crystal display (AMLCD) might be used as the basis of either direct or projected viewing: tiling of smaller displays (e.g. three 10 x 20 cm to create a large, 30 x 20 cm display; or projection from small, 5 cm, AMLCDs to create a 60 x 30 cm display.

Research directed at the creation of display technology required to support both the OLI and ILO approaches and, specifically, to support a PCCADS-capable cockpit design, including the simulator dome display re-engineered for implementation inside of a cockpit-scale capsule, is reviewed. Different parts of the display system will employ small, medium and large area technologies. In most cases, the military technology in each regime must, perforce, build on the commercial. Availability, one must recall, comprises usually not only the invention of a display technology but also several years of militarization and manufacturing process development.

2.3 Vision

The Joint Cockpit Office has developed technology visions for 1996, 2000, and 2020. These visions are depicted in Figures 5, 6, and 7.

Today's modern cockpit design is, essentially, the F-22 for a fighter, RAH-66 Commanche for a helicopter, and the C-130 RAMTIP for a transport or special operational forces (SOF) aircraft. RAMTIP is the Reliability and Maintainability Technology Insertion Program. Each pilot has 650-1300 cm^2 (100-200 in^2) comprising 2-6 color multifunction displays (MFD), of which any one of 2-3 can be designated as the primary flight instrument and the rest provide other mission or subsystem information as selected.

The 1996 cockpit vision includes a 650 cm^2 (100 in^2) full color flat panel tactical situation display and other flat panel displays, a limited Pilot's Associate (PA) system, and an all aspect HMD with 3-D audio displays. This concept is the "Mission/Task Adaptive Cockpit (MTAC)".

The vision for 2000 is a 2000 cm^2 (300 in^2) panoramic HDD coupled with a simple helmet control and targeting display. The HUD is absent in the 2000 vision as the head mounted head-up display and sight (HMDS) system completes its takeover of HUD functions, but in a vastly superior way due to its off-boresight acquisition/designation capability. The cockpit

canopy may be turned opaque to optical wavelengths[5] for mission segments flown within the threat envelopes from air, ground, or space-born visual anti-personnel laser weapons. A graphical world view is created from on-board digital data bases, the on-board sensor suite, and the off-board sensor suite. We here introduce the term synthetically generated view of the real world, or "sygvrew", for the imagery presented in the pilot's field of regard (FOR). This is to be contrasted to a view of an imaginary, or fictituous, world. The sygvrew for this 2000 system is of the OLI type. Data bases include pilot preferences, terrain, intelligence, and weather. On-board sensors include both passive (FLIR, GPS) and active (radar, lidar). Off-board sensors provide data linked information from other ships in the flight, JTIDS, AWACS, JSTARS, et cetera. This concept is the "Panoramic Cockpit (PC)", characterized by mature associate technology, wide FOV/color HMD, control by head/eye/voice, Pave Pace display generator, and cockpit-wide displays.

Visions beyond 2000 switch from the OLI to the ILO approach. One develops the sense that one is *inside* an artifically generated scene, or world, when the IFOV exceeds about 100° x 50°.

The 2020 vision is an encapsulated cockpit. The pilot may have no windows. His cabin may be a self-contained spheroid embedded within the aircraft or, possibly, elsewhere. The sygvrew presented in the pilot's field of regard (FOR) in this 2020 ILO system is much expanded over the 2000 OLI system. This display system might be that of a simulator--only better: projectors fill the inside of the sphere with a sygvrew centered on ownship. Alternatively, the sygvrew may be generated by a smafhired ("small format high resolution display"), or by a combination of display technologies. The sygvrew will be color and high resolution, perhaps in all parts of the sygvrew or just in the high resolution part of the IFOV (HIFOV). The pilot has the option of leaving, to some degree, or of removing entirely the real world visual effects of weather and night. The direct view display or helmet display may be designated the primary flight instrument with the other as backup. This concept is the "Super Cockpit (SC)" concept, characterized by pilot-state monitoring, machine learning, and 3-D virtual world (visual/audio/tactile) displays. The 2020 vision includes what some call virtual reality coupled with actual views from not only ownship, but also from a variety of other platforms via cameras, data bases, and data links. Two concepts for beyond 2000 are shown in Figures 6 and 7.

These visions incorporate an evolution to all aspects of the Super Cockpit, which augments present cockpit technologies with such things as graphics-generated views of the world, intelligent crew aiding, machine learning, pilot state monitoring, three dimensional displays, helmet mounted multifunction displays, and panoramic panel mounted displays.

2.4 Goal

Our goal is to fill the cockpit design requirement for a panoramic display. The opportunity to do so is arising from research and development conducted in our laboratory. Our strategy is to pursue multiple technological approaches: groupings (arrays or seamless tiling of flat panel displays) and projectors. We are funding, together with the Defense Advanced Research Projects Agency (DARPA) several different methods within each of these approaches. The engineering design opportunity will be realized on the flight line only if the pilot community accepts our vision. We expect that it will because of the environment in which future pilots are now growing up: panoramic video games and learning systems. They not only will accept panoramic HDD and HMD displays in the cockpit, they will expect and demand them. Our vision for the evolution of displays and display generators is shown in Figure 8.

2.5 Objectives

These displays must be readable in a variety of military situations. Examples include a pilot at 20000 feet on any day or on the desert/forest floor in a clear day, a tank commander, a field unit with a netted portable computer. The display must be suitable to all other light viewing conditions too, including the simultaneous use of night vision devices. Some specifics follow.

2.5.1 *Large area with high resolution*

Display modules must measure at least 25 cm (10 in) diagonal and have color pixel densities of at least 32 cm^{-1} (80 in^{-1}); or monochrome, 64 cm^{-1} (160 in^{-1}). Several modules or sizes can be grouped together as necessary to achieve the total aggregate display area required.

2.5.2 *Sunlight readable*

Persons with normal vision must be able to read the display in both direct and occulting sunlight. In each case the sun is not attenuated. Direct sunlight means the sun shines on the display; occulting, into the viewer's eye. The goal inherent in this requirement is usually expressed in terms of the luminance (light intensity) emitted and contrast maintained by the display for a specified illumination condition. Legibility must be established under full daylight. Full daylight for an open canopy fighter cockpit is taken to be an illuminance of either (1) 108000 lx (10000 fc) directly incident on the display with luminance of 1710 cd m^{-2} (500 fL) incident at the specular angle with respect to the test viewing angle, or (2) 21500 lx (2000 fc)

illuminance, with 6850 cd m^{-2} (2000 fL) luminance at specular. Full daylight for a partially closed transport cockit is taken to be the same, except that illuminance in the first case is taken to be 86100 lx (8000 fc). A contrast ratio must be at least 4.66:1 (5 grayshades) under the highest luminance condition and 10:1 under 40 % of the highest; the goal is 50:1 for all cases. These requirements translate, for example, to a display white field luminance in excess of 510 cd m^{-2} (150 fL); for video applications at least 750 cd m^{-2} (220 fL) is preferred so that 8 green monochromatic grayshades can be discerned.[6]

2.5.3 *Variable brightness*

Viewers must be able to adjust the brightness to be viewable in a continuum of over six orders of magnitude of ambient illuminance from 108000 lx down to 0.11 lx (10000 fc to 0.01 fc).

2.5.4 *Full color with gray scale*

Full color (8 frequencies spanning 380-760 nm) with 32 gray levels/shades per color is needed. Color pixels are quads comprising four square subpixels in an RG/GB or RB/BG scheme, triads comprising three square subpixels in an RGB scheme, or quads comprising four stripe subpixels in an YGBG scheme. The quad-square scheme with an NVG filter is preferred by the US Air Force and Navy; the quad-stripe without an NVG filter, the Army. The column drivers would need be capable of accepting only 5-bits per addressable pixel (monochrome pixel or color subpixel) and putting out 32 distinct voltage levels. Some are suggesting that a standard of 64-256 gray levels be adopted for the driver chips for flat panel displays. The higher number of levels than 32 are motivated by electronics considerations (64 would permit the use of standard, 8-bit bytes) and sensor considerations (256 might permit better display of FLIR images).

2.5.5 *Night vision compatible*

No significant intensity may be emitted from the display into the FOV of the night vision sensor. Night vision goggles (NVGs) integrate the sensor into the HMD, which means that HDDs and HUDs will blind the viewer if they emit significant light energy in the NVG band. Generation three (GenIII) NVGs amplify 600-900 nm (Class A) and can be used in starlight and overcast conditions. This requirement typically translates to a special, additional filter in a full color AMLCD display. One must sacrifice some night sky intensity (10% star, 25% moon) to retain red (about 630 nm) in the display; this is accomplished with two filters: (1) one in the display to limit its emission spectrum to wavelengths less than about 650 nm and (2) a 665 nm "minus blue" cut-off filter in the NVG to limit its acceptance spectrum to 665-900 nm (Class B).[7] Alternatively, one can give up red entirely to completely maximize the use of the available night sky illumination in the red and infrared; one then has a yellow-green-blue (YGB) three color display rather than a full color, red-green-blue (RGB) display. The ultimate solution is to achieve night vision *without* NVGs: an imaging infrared camera is slaved to the instantaneous pupil direction and its image relayed through a video memory/processor to an HDD or HMD. The trade-off is, thus, avoided and one retains both full color HDD capability and complete use of available night sky illumination.

2.5.6 *Environmental and Other*

Military environmenal and other specifications must be demonstrated by testing.[8]

3. TECHNOLOGICAL APPROACHES

Technological approaches to large area, or panoramic, cockpit displays include array, tiling, and projection. Arrays are known commercially by such names as video wall. Tiling retains several individual displays, as in an array, but removes the spaces between them. Tiling can be accomplished by several methods: butt-coupling; circuit pasting; optical stitching.

3.1. Array

The "glass cockpit" was first made possible by CRTs. We are now upgrading to more capable electronic displays based on flat panel technology. An array, or grouping, of electronic displays based on current technology can produce a cockpit instrument system which is a close approximation in flight hardware of the PCCADS 2000 concept.

3.1.1 *Cathode tubes*

Military avionic CRTs have problems with reliability, availability, sunlight readability, and scalability. Also, CRTs cannot be scaled to 2000 cm^2 with space, weight, and power supportable in an aircraft. Research in areas like flat-neck CRTs may provide new options, however.

3.1.2 *Flat Panel*

AMLCD is the only flat panel display technology currently capable of high brightness (sunlight readable) and full color. These displays are under development for new systems and retrofit programs. The F-22 HDDs comprise some six a-Si AMLCDs of dimension 20 x 20, 16 x 16, 10 x 8 cm (8 x 8, 6 x 6, 4 x 3 in.) with 200 cm^{-1} (80 in^{-1}) color pixel density, and with a total area of some 1300 cm^2 (200 in^2).[9] The RAH-66 HDDs comprise two each 20 x 15, 10 x 10 cm (8 x 6, 4 x 4 in.) a-Si AMLCDs for a total of some 825 cm^2 (128 in^2) in each cockpit (fore and aft).[10] The C-130/C-141 retrofit program will install several 15 x 20 cm (6 x 8 in.) AMLCDs having color pixel density 200 cm^{-1} in each transport cockpit; a Reliability and Maintainability

Technology Insertion Program (RAMTIP) is underway[11] in which a complete cockpit retrofit of a C-130 aircraft has been accomplished with some six 15 x 20 cm (6 x 8 in.) a-Si and CdSe AMLCDs providing 775 cm^2 (120 in^2) per pilot and 310 cm^2 (48 in^2) for the navigator.[12] The avionic AMLCDs for the two new systems and for other programs are being manufactured by Optical Imaging Systems in Troy, MI.[13] Hosiden in Japan and Sextant in France have also fabricated a-Si AMLCDs for various military avionic research programs. Rockwell Collins has demonstrated a video rate 20 x 15 cm (8 x 6 in.) color AMLCD driven by a third-generation video generator and software that allows a range of 100 gray shades.[14] Texas Instruments has developed military versions of its LCD drivers to operate displays in aircraft, armored vehicles, field computers, or targeting systems.[15] Thus, AMLCDs can support forward looking infrared (FLIR) and television video with motion including graphics. Schematics of the F-22 and RAH-66 EMD cockpits are provided in Figures 9 and 10. Figure 11 is a photograph of the C-130 RAMTIP cockpit; Figure 12 is a photograph of one of the Litton displays used in RAMTIP with the drivers and connectors shown.

Thompson[16] at Xerox PARC in Palo Alto, CA has established a prototyping facility which is now developing a robust, high definition AMLCD technology with a-Si and p-Si TFTs.[17] Xerox plans to design and fabricate high resolution AMLCDs having large display area using a-Si and to research large area substrates 36 x 33 cm (14 x 13 in.) using p-Si semiconductor material. Thompson presently sees packaging as the main problem, with multichip designs of chip-on-glass (COG) and tape automated bonding (TAB) interconnects now, and integrated drivers, later. A universal controller for AMLCDs will be fabricated in 1992. Thompson is now scaling up the p-Si work from small area 15 cm (6 in.) square to large area 36 cm (14 in.) square. Xerox works with Standish Industries Inc in Lake Mills, WI for LCD processing.

Litton in Canada is researching AMLCDs using CdSe instead of Si for the semiconductor layer.

Research on other technologies may eventually lead to additional flat panel options. The problem has been primarily with the generation of the blue required for full color displays. True-blue LEDs which are bright and efficient should be available for the display designer in the near future.[18] Stanley Electric Co. has an 470 nm LED (using silicon carbide as the light emitting material) on the Japanese market, and Sharp Corp. will introduce a blue LED when luminance increases by an order of magnitude. Some 130 mcd at an efficiency of 0.8% has been achieved at Nagoya University and will be commercialized by Toyota Gosei Co. Efficient red, yellow, and green LEDs are widely available, largely as a result of using GaAlAs material.[19] A full color electroluminescent display (ELD) has recently been developed by Planar of Beaverton, OR; again, blue has been the problem with 32 lm (3fL) at 60 Hz having been demonstrated.[20] The display is presently bright enough to be read in dim ambient light. Neither LEDs nor ELDs will be available as a full-color sunlight-readable display technology for many years.

An active matrix microtip phosphor display (AMMPD) is another possibility. Here matrix addressing of the microtips controls the intensity of electron excitation of pixels comprising phosphor dots or squares.

3.2. Tiling

The full PCCADS concept of a seamless PCD of 2000 cm^2 requires a significant expansion of the current state of the art in display technology. One approach is to move the current discrete displays so close together that one perceives one large display rather than several discrete multifunction displays. In this way the same windows as now can be presented and it becomes possible to present a seamless panoramic display across the tiled array yet retaining redundancy. The state of the art is represented by the 6144 x 2048 pixel; 152 x 51 cm (60 x 20 in.) prototype built from three 2K x 2K CRTs by Masuishi, Small, and MacNeil[21] at MIT in Cambridge, MA, who have introduced a virtual framebuffer architecture to enable implementation of two kinds of seamlessness in tiled systems (CRTs are used here for research purposes).

3.2.1 *Butt-coupling*

Stewart[22] at the David Sarnoff Reseach Center (DSRC) in Princeton NJ is working on a program for which the original goal was to develop a 30 x 20 cm (12 x 8 in.) display having 1200 x 800 color pixels (960000 pixels @ 100/in.) comprising three 10 x 20 cm (4 x 8 in.) p-Si AMLCD panels. DSRC is now working with Standish to complete a video rate demonstrator using a single panel in the portrait 20 x 10 cm (8 x 4 in.) orientation. DSRC has done the design, is doing the electronics, and will produce the active and passive glass; Standish will do the fill and seal.[23] DSRC will then integrate and deliver the demonstrator to the Wright Laboratory. This panel features integrated drivers and field sequential full color. The integral drivers ("self-scanning" display) reduce the external lead count from 2400 to 46 per panel. This butt-coupling approach to create a large area display is illustrated in Figure 13.

Firester[24] at DSRC is starting design of a large area 36 cm (14 in.) diagonal, self-scanned XGA color display in p-Si. The XGA video standard comprises 1024 x 768

pixels, each capable of 256 colors non-interlaced. In addition, DSRC will be designing a 256 grayshade data line driver (40 MHz, 20 V) for a-Si XGA LCDs to be fabricated as a standard cell in a library for an application specific integrated circuit (ASIC).

Scott[25] at Magnascreen in Pittsburgh, PA is using a different tiling approach. The research plan calls for a demonstration in the form of an 8 x 6 array of 13 x 13 cm (5 x 5 in.) passive matrix twisted nematic (TN) liquid crystal panels. The viewer will perceive the mosaic to be a single display measuring 104 x 78 cm, or 130 cm diagonal (41 x 31 in., or 51 in. diagonal) and consisting of a total of 640 x 480 color pixels (16 colors). If the Magnascreen approach works, it can be used to tile other types of panels, such as AMLCDs.

3.2.2 *Circuit pasting*

Pasted circuit arrays can be created by placing several individually fabricated circuits together on a large substrate. The large, pasted circuit is then to be driven as if fabricated at one time. The objective is to use the high temperature processes necessary to produce circuits in p-Si and x-Si (silicon substrate) followed by transfer to the glass substrate for display assembly. Several AMLCD circuit transfer demonstrations have been accomplished by Kopin in Taunton MA using DSRC Color Matrix Display panels (p-Si and x-Si, 5x5 cm, 192x192 monochrome pixel) with assembly by Standish. Such an x-Si panel has been successfully operated. Pasting several of these smaller displays together into a large display may be attempted next.[26]

3.2.3 *Optical stitching*

Stitching involves optical means to make the physical display structure comprising the discrete pixels and individual displays appear to be one large display by optical interconnection schemes.

Macro-coupling makes a segmented display array appear to be one large, unsegmented display. One means of accomplishing this which has been tried involves optical fibres, often with one fibre per pixel. Fibre-coupled displays have not demonstrated a visually acceptable seam. Abileah and Yaniv[27] have tested a method involving a diverging glass fiber-optic faceplate (plastic and micro-channel (hollow pipes) faceplates might be used instead); any number of displays may be tiled, but there is a 20% loss in resolution.

Micro-coupling bends rays emanating from each pixel of each subdisplay so they have, from the viewer's perspective, a continuous pixel pitch. Micro-lenses and micro-gratings are fabricated by standard photolithographic techniques. One implementation might be a sheet of miniature optical elements, one per pixel. Cox at Honeywell in Bloomington MN and Shvartsman at DuPont in NJ have teamed to develop such a microlens array which might be applied to tile any flat panel.[28] A hologram might also be used to implement the same stitching effect as provided a sheet of optical elements.

Marrakchi et al.[29] at Bellcore in Red Bank, NJ are using two-dimensional SLMs to make micro-lense and micro-grating arrays programmable. The reconfigurable optical crossconnection technology may help in the optical stitching method of tiling flat panels.

3.2.4 *Combined technologies*

Buzak[30] of Tektronix in Beaverton, OR is developing TekVision™, a plasma addressed liquid crystal (PALC) display technology. In this novel design, the active matrix addressing is implemented with ionized gas (plasma) confined in channels rather than the more commonly used TFT, MIM, or diode. Plasma was used to address polymer dispersed liquid crystal material in early work, but twisted neumatic liquid crystal material is used now for the direct view application. A PALC panel comprises the LC and a protective dielectric layer between upper and lower glass sheets. The upper sheet is patterned with data electrodes; the lower, with channels (grooves) containing two parallel electrodes for anode and cathode. The objective is the definition and development of high volume manufacturing techniques for displays characterized by flat panel depth < 5 cm (2 in.), large image size > 38 cm (15 in.) diagonal, 24 bit full color, and >16 kHz line rates to support video. Work is currently underway on a 40 cm (16 in.) diagonal demonstration panel. Because of the simple electrode structure with all lines running edge-to-edge across the complete display, PALCs should be readily scalable to PCCADS size (2000 cm^2).

4. PROJECTION

There are several projection methods: cathode ray tube (CRT), liquid crystal light valve (LCLV), deformable mirror device (DMD) chips, active matrix liquid crystal display (AMLCD), lead lanthanum zirconium titanate (PLZT) devices, electron-beam-addressed membrane light modulators (e-MLM), and solid state laser display (SSLD). Blaha[31] has recently reviewed other large screen display technologies. Projector light power output is given in watts at the aperture or lm at the screen; one must specify a projection solid angle to compute luminance or a screen size to compute illuminance.

4.1 CRT and LCLV

Cathode ray tubes and light valves have been used in projectors for some time. The CRT displays are of much lower quality than the LCLV. Militarized versions of both technologies are expensive, heavy,

power-hogs of low reliability. Present applications include command/control centers and simulators. An example is the new Hughes Series 300 LCLV system, based on an optically written a-Si photoconductor, which projects 2500 lm at video rate with good contrast for a price of $150,000; additional limitations include low frame rates and thermal sensitivity.

4.2 DMD

Deformable mirror devices present a near term practical alternative to the CRT and LCLV projectors for applications not requiring small weight and space. Younse and coworkers[32] at Texas Instruments (TI) in Dallas, TX is developing DMD technology for a variety of products, including printers and high definition displays. A 768 x 576 pixel PAL DMD chip has been fabricated, and a PAL/NTSC live-video projector will be demonstrated en route to the high definition display. Early test chips show excellent grayscale and color and a 140:1 contrast ratio; the breadboard optics system is delivering 560 lm monochrome B/W to the 152 cm (60 in.) diagonal screen of area about 1 m^2, or about 560 lx. Color is presently achieved using frame sequential operation of the DMD and a rotating color filter wheel, bringing color illumination to about 185 lx. A 3-DMD color optics design is being considered. The prototype projection optical subsystem with a 500 W source producing >1000 lm is being developed by DSRC. The mechanical durability of the mirror hinges is being investigated by Pryputniewicz[33] at Worchester Polytechnic Institute in Worchester MA. The prototype 1940 x 1080 pixel, high definition display system incorporating a 3.2 x 1.9 cm (1.25 x 0.75 in.) DMD chip with a 16:9 aspect ratio, a 150:1 contrast ratio, and projecting >1000 lm to the screen is to be demonstrated in late 1993. DMD projectors may find applications as transport and bomber aircraft PCD prior to miniaturization of the light source.

4.3 AMLCD

Liquid crystal displays can be used in projection as well as direct view. The overall efficiency requires improvement and is being addressed using a prototype LCD projector by Glenn[34] at Florida Atlantic University in Boca Raton, FL; a high resolution, high brightness color projector is scheduled to be demonstrated in 1994; lenticular lens plates are registered with pixels to improve efficiency (by a factor of 4) and to reduce heating. Xerox has announced a 525 x 525 pixel, 3.8 cm (1.5 in.) square, p-Si on quartz AMLCD for projector applications. DSRC is considering the application its self-scanned high density (800 dpi) AMLCD technology, which involves p-Si on glass and quartz substrates, to projectors.[35] Schwarzer[36] at Hughes in Carlsbad, CA has developed the Hughes HighBright™ cockpit display based on three a-Si AMLCDs operating in a color projector design; the breadboard system is sunlight readable and has an active display area of 16 x 16 cm (6.25 x 6.25 in.). The size, weight, and power requirements of the light sources for these projectors all need reduction; they are brighter than CRTs, but otherwise may provide little improvement at present.

4.4 PLZT and e-MLM

The LCLV, DMD, and AMLCD are all spatial light modulators (SLMs). Additional SLM designs are being considered for the projector application. Gobeli[37] at Foresight, Inc. in Winter Park FL is evaluating PLZT as the basis of a projection display and may develop a high brightness, high resolution display based on PLZT. Ward and coworkers[38] at Optron Systems, Inc. in Bedford, MA have studied the application of their e-MLM device to projectors and conclude that a 1280 x 1024 pixel monochrome prototype would deliver 2000 lm to a >132 cm (52 in.) diagonal screen with a contrast ratio of 300:1 with a 60 Hz frame rate. Considerable work remains before such technologies might be considered for cockpit applications. For example, the e-MLM approach would require three of everything to achieve color, including high-brightness lamps, e-MLM devices, and optics.

4.5 Laser

Lasers present a very promising technology for achieving panoramic cockpit displays. Laser light is coherent and colors are fully saturated. The coherency translates to a unique feature of laser displays: virtually infinite depth of focus. This means that the image is always in focus, even when displayed on curved or domed screens, as in a custom installation inside a cockpit or simulator. The pure colors provide a wide color spectrum capability. The color range is larger than CRT or LCD based systems. Furthermore, a laser display has better legibility: objects which are fuzzy in a CRT or LCD system are clear in a laser projection of the same image size. Laser display technological approaches include discrete lasers (both gas and solid state), laser arrays (solid state), and a CRT having semiconductor materials in place of phosphors. The various solid state approaches vary in the pumping mechanism.

4.5.1 ***Gas/Dye***

A gas/dye laser projector was developed by Visulux in 1986 for the U.S. Air Force.[39] The system was designed to produce an image size from 6-12 m (20-40 feet) wide and have a lifetime of 10000 hr at 3000 lm equivalent incoherent light brightness. Some 18 of these large screen display systems were sold at about $250K each; most were used in command/control centers. HQ MAC used the system to produce a 3.67 x

9.8 m (12 x 32 ft) picture of the world and to project where all its airplanes were; when they doubled the size of an area on the map they got the same resolution and picture quality all across the screen. These projectors are remarkable in their performance but require too much space, power, weight, and cooling for use as an airborne display. The projector weighs 270 kg (600 lb) in a space of 1.4 m^3 (48 cu.ft.), and runs on 3 phase 480 VAC power. In addition to command and control centers, such projector systems may also be appropriate for use in simulators and other ground-based platforms where the support requirements of gas/dye lasers are not prohibitive.

4.5.2 *Solid State*

Solid state lasers (SSLs) present an attractive method of achieving a PCD. The three primary colors are to be produced by direct SSL lasing at the visible frequency where possible, or else by frequency doubling of near infrared SSLs. Such a device might require but 0.025 m^3 (<1 cu.ft.) and be some 5% efficient in converting electrical power to light on the screen.

Nitor Corporation in San Jose, CA is pursuing an approach based on red, green, and blue semiconductor lasers with optimized source wavelengths, solid state modulation, and electromechanical scanning.[40] A red laser at 640 nm has been developed, blue has been demonstrated, and green is under development. Each of the primary colors (red, green, and blue) is modulated and combined into white (tri-color) light and raster-scanned across the screen. The optical design has been simulated, and the electronics design is complete. The schedule is for monochrome NTSC and RGB high definition prototypes by 1993. The color prototype is to project up to 1920 x 1035 tri-color pixels in an image size of 1-5 m (50-200 in.) diagonal, have a contrast ratio of 150:1, require wall plug power, have a lifetime of 40000 hr, and have a brightness (equivalent incoherent light) of 1800 lm. The Nitor solid state laser projector design is summarized in Figure 14.

Several SSL approaches are being pursued for production of all three primary colors. One class involves rare earth doped garnets pumped with infrared diodes. McFarlane[41] at Hughes in Malibu, CA is performing materials research necessary for this method to proceed. Hughes is working on visible upconversion lasers and plans to make an all solid state, diode pumped RGB laser system for projection and other applications; 0.5 W has been achieved at 551 nm with pumping at 797 nm, and 1.1 W is projected. Another class of visible laser technology is the vertical cavity surface emitting laser (VCSEL) based on molecular quantum wells structures fabricated from GaAlAs/GaAs. Also, laser diode arrays are already used to produce sufficient power, albeit in the infrared. These latter approaches can produce red directly but requires frequency doubling, or other inefficient energy conversions, to achieve green or blue.

Significant research remains before visible solid state lasers are ready for displays. Blue is the biggest challenge: only 10-100 mW of light output has been demonstrated to date. Harrison[42] at Schwartz Electro-Optics in Concord, MA, for example, has studied the second harmonic generation problem for DARPA using a frequency doubled, diode laser pumped Nd:YAG laser operating at 473 nm and concluded that alternative configurations must be considered to achieve sufficient power at a blue wavelength.

4.5.3 *E-Beam Pumped Semiconductor*

Another full color SSLD method is an e-beam pumped semiconductor (EBS) laser fabricated as a two-dimensional array in a CRT with II-VI materials (CdSe-red, CdS-green, ZnSe-blue) in place of the phosphors. Such devices provide laser emission from more than 1000 x 1000 randomly addressable spots.[43] Other materials, including GaAs, are being tested owning to the poor lifetime characteristics of the II-VI materials. Bhargava et al.[44] at North American Philips in Briarcliff Manor, NY have reviewed this approach for large area projection TV displays. Rice[45] at McDonnell Douglas in St Louis, MO is considering developing the RGB laser video projector developed within the last two years by Nasibov et al. at the Lebedev Institute in Moscow, Russia. The EBS approach might be made useable in a cockpit if the pumping were provided by a matrix addressed variation of the flat, micro-tip field emission plate currently being considered for application in LCD backlights.

5. SMALL FORMAT DISPLAYS

Research is presently underway to establish a small format high resolution display, or smafhired, technology capable of presenting video rate imagery (real or virtual) in applications requiring ultra low weight and power, such as a helmet. A 1280 x 1024 pixel monochromatic full grayscale smafhired would satisfy some 80% of the identified DoD requirment for HMDs if the active area were 2.5 cm (1 in.) square in a 5 cm (2 in.) package.[46] For future applications it is noted that the IFOV required to support ILO systems is 120 x 60° with a 4pi sr FOR with a resolution of 1 mrad. Applications for smafhireds include not only military HMDs, but also commercial (personal video, telecommunications, arcade games, computer displays, etc.).

5.1 PCCADS HMDS

Current HMDS technology permits the pilot to use head pointing to position sensors and seekers in directions

outside of the HUD FOV, thereby giving him quicker first shot capability. The Agile Eye system produced by Kaiser was used by McDonnell Douglas in the PCCADS program. The lead pilot had a 12° IFOV to designate visual targets and to provide HUD type information on the helmet visor. The pilot FOR was that of his head range of motion. A 1.3 cm (0.5 in.) diameter CRT, the high voltage supply for the CRT, the optical elements necessary to project the CRT image onto the visor, and the head tracker receiver were incorporated into the helmet. An HMDS system is under consideration as a growth capability for the F-22 air superiority fighter. A day only HMS is being developed for the F-16 as a retrofit item. The Sextant Avionique/Intertechnique lightweight helmet with integrated sight and display has been selected for use on the French Rafale combat aircraft.[47] These systems represent today's technology and provide graphics but no video.

Smafhireds will provide video. Because the smafhired is mounted inside an HMD, 43000-65000 lx (4000-6000 fL) luminance is required for the most demanding application.[48] Less is required at night or at such times as the canopy is opaqued, but most mission segments will be flown with clear canopy to take advantage of that fantastic real world display provided by nature. Accordingly, micro CRTs, AMELDs, LEDs, etc. may compete successfully with AMLCDs and SSLDs in this application only if they too can satisfy the sunlight readibility criterion.

5.2 Miniaturized CRT

Smafhireds presently take the form of the miniaturized CRTs developed over the past 15 years under the Armstrong Laboratory computer created view research program. These devices are still too heavy for a fighter pilots pulling high G-loads and soldiers fighting for hours. System integrators such as Kaiser[49] of San Jose, CA and S-TRON[50] of Mountain View, CA are evaluating small format CRTs, but are looking to flat panel and other technologies for less weight and power with more resolution and color.

5.3 Flat Panel

Smafhireds might be realized with much the same flat panel technology as for HDDs. A program to miniaturize flat panels for application in military avionic HMD systems is being undertaken by this office; our projected emphasis is the AMLCD approach. The Army is working on smafhireds under its Soldier's Integrated Protective Ensemble (SIPE), Combat Vehicle Crew (CVC), and other programs.[51] System integrators are considering the use of lighter weight flat panel displays instead of CRTs as smafhireds in HMDs. Kopin is developing x-Si AMLCD/AMELD smafhired technology. Also, DSRC is considering development of the necessary LCD technology; Planar of Beaverton, OR, the ELD technology.

5.4 Laser Retinal Painter

The terminology "laser retinal painter" is hereby introduced to cover a new class of HMD: an image generated by a very low power laser beamed through the pupil and scanned across the retina. The scanning and modulation of the laser is controlled by solid state devices, such as acousto-optic modulators. Furness[52] at the University of Washington in Seattle began experiments on such a system in January 1992.

5.5 Visor Projection and Other Approaches

A variety of other approaches are being explored to take smafhireds from concept today to technology tomorrow. Many of these approaches involve projection on the inside surface of the helmet visor. The projection concept is as follows. The system tracks the pupil as well as the head position and projects high resolution information in the center 5° HIFOV for direct vision and low resolution information into the full 120° IFOV peripheral vision. The content of the IFOV is based primarily on head position; the content of the HIFOV, pupil. Motion cues in the IFOV are used to direct the viewers HIFOV scan of the virtual reality presented by the smafhired system. The HDD projector approaches discussed in Section 5 above might all be miniaturized, in principle, to provide a variety of smafhired projectors for evaluation in PCD systems.

6. MULTIPERSPECTIVE CAPABILITY

Part of our vision for 2000 is a capability of the display to operate in a multiperspective mode. That is, the display can be switched to show terrain or threat data, for example, in full 3-D. This capability will increase pilot situational awareness by providing realistic 3-D display of information to the pilot when needed. Multiperspective means hologram, or hologram-like, enabling the viewer to look around objects and to view them from a wide range of angles. Aviation applications have been reviewed by Wickens, Todd, and Seidler.[53] Hopper[54] has reviewed hardware approaches to 3-D which have promise of being eventually applied in a cockpit. Some examples follow.

6.1 Autostereoscopic Flat Panel

Eichenlaub[55] at Dimension Technologies, Inc. (DTI) in Rochester, NY is advancing an LCD based autostereoscopic display technology for the Air Force. Two perspectives, one per eye, are produced using stereoscopic display format generators and a head tracker is used to determine the instantaneous perspective set sent to the HDD. The DTI display device is capable of displaying real time video

information, as well as computer input, and is switchable between 3-D and 2-D modes. The first product has been developed: a stand-alone 640 x 480 color pixel 3-D LCD which accepts input from IBM PC, Apple MAC, or TV cameras. It will produce 8 bit, 32768 colors from 200W or less at 30 frames per second on a 30 cm (10.2 in.) diagonal screen which is easily readable in 108000 lx (10000 fc) ambient light at a contrast ratio of 100:1. The head tracking is soon to be upgraded from electromechanical to electro-optical. A second product in development will provide autostereo capability and full horizontal resolution to both eyes. Work on a high resolution display has begun to enable the viewer to see the full resolution from all locations, thereby providing multiperspective capability for PCD-sized displays. The DTI autosteroscopic 3D display is illustrated in Figure 15.

6.2 Volumetric

Laser addressed volumetric displays provide another route to multiperspective cockpit displays. The enabling technology is being developed by Williams and Garcia[56] at Texas Instruments in Dallas, TX (OmniView™) and by Soltan[57] at the Naval Ocean Systems Center in San Diego under joint Navy and Air Force funding. In both cases lasers project the image onto a rotating helix screen and points are plotted in X, Y, Z space to provide a real spatial image. All possible perspectives (3-D views) are provided in a single spatial image (one just moves around the display object). The largest TI custom volumetric display addresses 4096 x 4096 x 4000 volume elements (voxels) of 2.5 mm size contained in a cylinder 0.91 m in diameter by 0.46 m height (36 in. D, 18 in. H). Some 4000 voxels per color can be projected at any one time: 4000 white display voxels; or 4000 each of red, green, and blue for a total of 12000 color display voxels. The NOSC display under development has as objectives the projection 35000 voxels in a 33 cm (13 in.) diameter double helix use solid state lasers on a 3-D display media with no moving parts. A charactericstic of these volumetric displays is that there are no hidden lines: all image formats must be designed to be viewable from all directions with no hidden line removal.

6.3 Hologram Projection

Benton and coworkers[58] at the the MIT Media Laboratory in Cambridge, MA are researching the display of computer generated holograms (CGHs) of 3-D objects. Hologram sequences have been computed on the Connection Machine Model 2 supercomputer and transmitted via a data network to the laboratory computer for playback with a laser through a spatial light modulator (SLM) having one physical dimension. Vertical parallax is sacrificed to speed up the computations and make it possible to project the holograms line by line through acousto-optic modulator (AOM) cells. Good quality images which exhibit excellent color registration can be projected by illuminating 3 AOMs with 633 nm (red), 514 nm (green), and 442 nm (blue) laser light. A 6 megasample holographic pattern (one frame) can be computed in <1s from an image comprising 1000 points with arbitrary intensity. Farhoosh et al.[59] have used an SLM having two physical dimensions comprising an LCLV in contact with a CRT via a fiber-optic plate to achieve a 3 frame holographic movie with a display rate of 1 frame per second. Many years of work remain before hologram projection technology might be available for cockpit application.

7. SYSTEM CONSIDERATIONS

The PCD is part of the cockpit displays and control system. A small supercomputer, known as a graphics processor (GP) is necessary to drive such a large area electronic display system; similarly, special processors are required to implement pilot decision aiding systems. Clearly, the functions and screen formats must be determined for this new class of displays.

7.1 Graphics Processor

A supercomputer in a shoebox is required to drive the PCD displays. All information must be integrated in standard formats and graphic generated for the large area of high resolution display surface(s). This office is developing this display engine under a program entitled Cockpit Display Generator (CDG), comprising several contractual and in-house research projects. Myers[60] has published an overview of the program. The definition phase has just been completed.[61] In addition to electronic processing circuits, optical processing circuits may be employed to reduce the size and weight of the on-board processor. Hopper[62] has reviewed international work in optical computing and processing.

7.2 Information Processor

Pilot's Associate (PA) is the information processing aid which determines which data is sent to the graphics processor and, thence, into the aforedescribed display formats. Banks and Lizza[63] have explored the lessons learned in building a cooperative, knowledge-based system to help pilots make decisions.

7.3 Display Format

Reising and coworkers[64] have investigated the application of color graphics and large screen flat panels to information display in military cockpits. They strongly advocate use of color pictorial formats to provide intuitive presentation and, thereby, a potential reduction in pilot workload. A large display is critical to integrate all information in a meaningful, legible way. Future electronic multifunctional displays (MFD) must

deliver both color and large area to support the display format requirements. Reising and Emerson note that one day the entire instrument panel may consist of one display surface where both pictorial and alpha-numeric formats will be displayed. The large HDD system may be augmented with a virtual cockpit where the instrument panel, as it is known today, is replaced by images of the instruments projected on the pilot's visor. They also recommend three-dimensional (3D) capability for some display formats.

8. DISCUSSION

Modelling efforts will be necessary to evaluate the new PCD technologies as they evolve against requirements, and fields other than aircraft must be monitored for synergistic developments.

8.1 Hierarchical Modelling/Simulation

A set of hierarchical models are being developed for use in display design and evaluation. The technologies described here can be used in a myriad of ways against PCD objectives. Modelling includes simulation and will reduce the number of costly fabrication and testing projects necessary to evaluate the possibilities against all key user considerations (functionality, compatibility, producibility, availability, reliability, maintainability, affordability). This is a complexity analysis problem and requires hyperspace modelling. The display level (functionality) model comprises submodels of both man and machine; the development of such a model is being performed by a multi-institutional team lead by Larimer at NASA Ames at Moffett Field, CA.[65] Demand models will track the ever-changing requirements for sunlight-readable displays in military systems; development of this model is being lead by Hopper.[66] The producibility model contains representations for processes, equipment, operator training levels, etc.; one widely available model is that produced by Resor[67] at MRS Technology Inc. in Chelmsford, MA. Breadboards at several hundred thousand dollars each, nor factories at several tens to hundreds of millions each, can be built just to try out the possibilities. Modelling is much more effective and will become our display evaluation tool for the 1990's and beyond to maximize what we learn from each breadboard and flight test and to minimize the number which are necessary. Accordingly, a hierarchical modelling effort incorporating all appropriate models/simulations is being undertaken for cockpit applications by our office.

8.2 Synergistic Applications

Other applications exist in the area of optical processing and computing for the smafhireds needed for HMDs and for the spatial light modulators used in some projector and 3-D display approaches Advancements in such areas will expedite the development of PCD technology.

9. CONCLUSIONS

The advantages of a large area display system were recently demonstrated in the Panoramic Cockpit Control and Display System program, a joint research effort of the Wright Laboratory and Armstrong Laboratory. The key objective result was a 45% increase in pilot combat effectiveness, which translates to a 31% reduction in the number of aircraft and pilots needed for a given mission. The price is the development of display hardware necessary to put such display systems into operational aircraft. As airplanes and pilots cost several orders of magnitude more than the research and development program required, significant cost savings will result--more defense for less money.

An array of AMLCDs has provided an approximation of the panoramic display concept. Such an array is the realization of our present cockpit vision. Several systems now in EMD have selected this approach, including the F-22 air superiority fighter, the RAH-66 light attack helicopter, and the C-130/C-141 transport retrofit program.

The 1996 vision will most likely be realized by an evolution of present AMLCD technology to larger, 625 cm^2, areas per display combined with tiling techniques. Such techniques are a natural extention of todays technology and are expected to dominate for the foreseeable future. Autostereoscopic 3-D technology will be available for use with flat panel displays.

Solid state lasers present what is, perhaps, the most attractive alternative for achieving panoramic cockpit display technology by 2000. They are light in weight, low in power requirements, and can meet all environmental requirements more readily than the other methods discussed. Further more, they can scale from HDD down to HMD sizes and up to dome size. Also, applications of projectors extend beyond to aircraft cockpits to simulators and training aids. Small format display technology requires significant research before high resolution images in helmet systems become a design option. Smafhireds with 1280 x 1024 pixels will be available for application as a monochrome HMD with 60° x 60° IFOV and as color projector for HDD instruments. Multiperspective (true, full, look-around 3-D) technologies will be available for application in HDD systems; the HMD system will be capable of providing autostereoscopic (one perspective per eye) formats. Multiperspective display development is fast making true 3-D a cockpit design option.

By 2020 a variety of projector and direct view technologies will be available to build HDD and encapsulated cockpit display systems. Individual HDDs will be 16 million (e.g. 4096 x 4096) color pixels in

2000 cm^2 (300 in^2) and contoured to fit the curved surfaces of the control panel and inner canopy. Several of these HDDs will be tiled to achieve larger display areas. Smafhireds will be 120° x 120° IFOV with 2048 x 2048 monochrome pixels (1.02 mrad spots), and full color capable. Both the HDD and HMD system will provide multiperspe.tive 3-D capability where useful in the cockpit display format design.

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Figure 1. PCCADS 2000 concept.

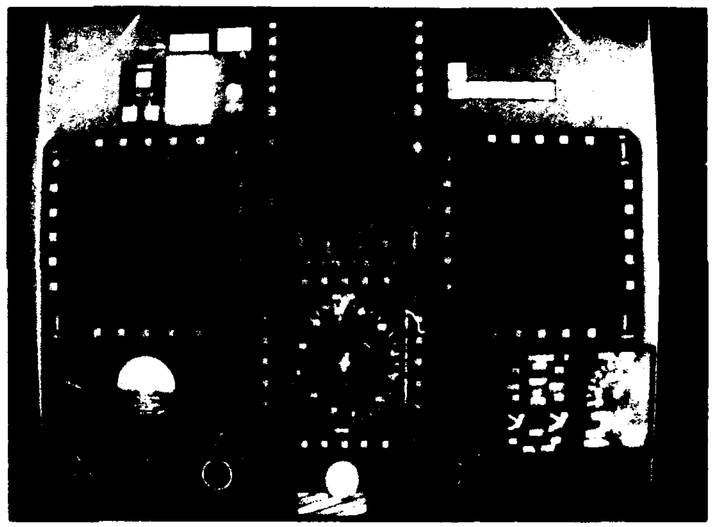

Figure 2. Simulation of F-15E displays.

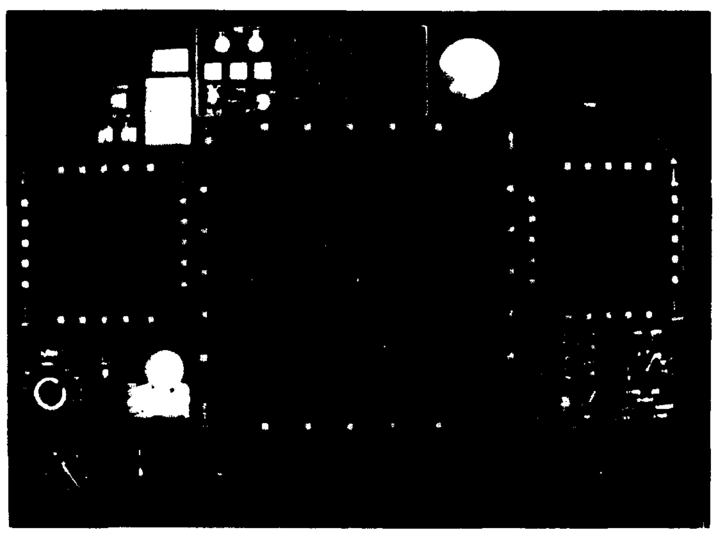

Figure 3. PCCADS 2000 displays.

Figure 4. PCCADS test cockpit: improved man-machine interface via large display plus HMDS.

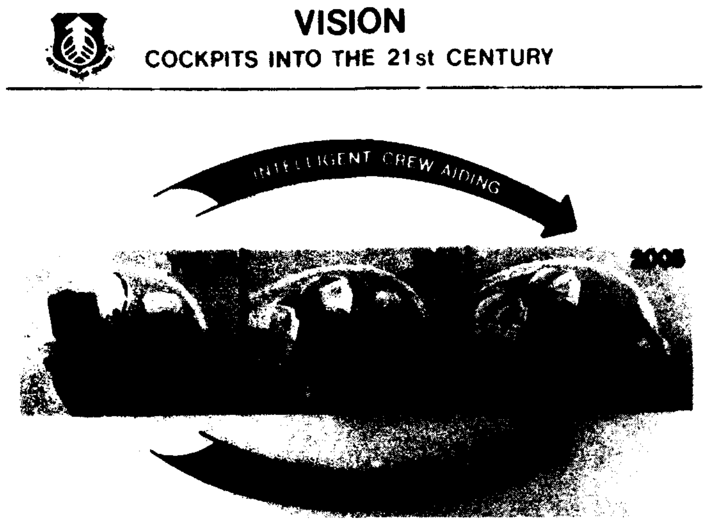

Figure 5. Joint Cockpit Office visions for today, 1996, and 2005.
Note: the technological capability to implement the 2005 vision is now expected by 2000.

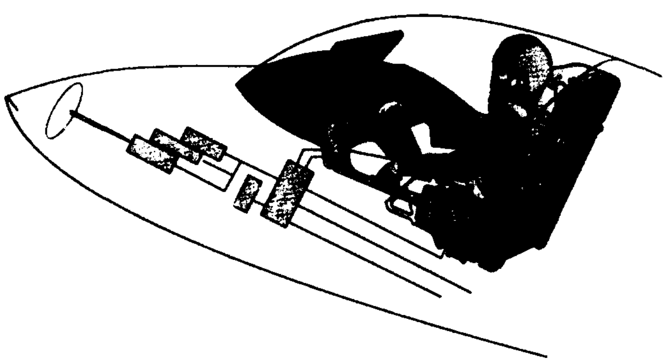

Figure 6. Panoramic cockpit concept for beyond 2000 *with* retention of a bubble canopy.

Figure 7. Encapsulated cockpit concept (courtesy of McDonnell Douglas).

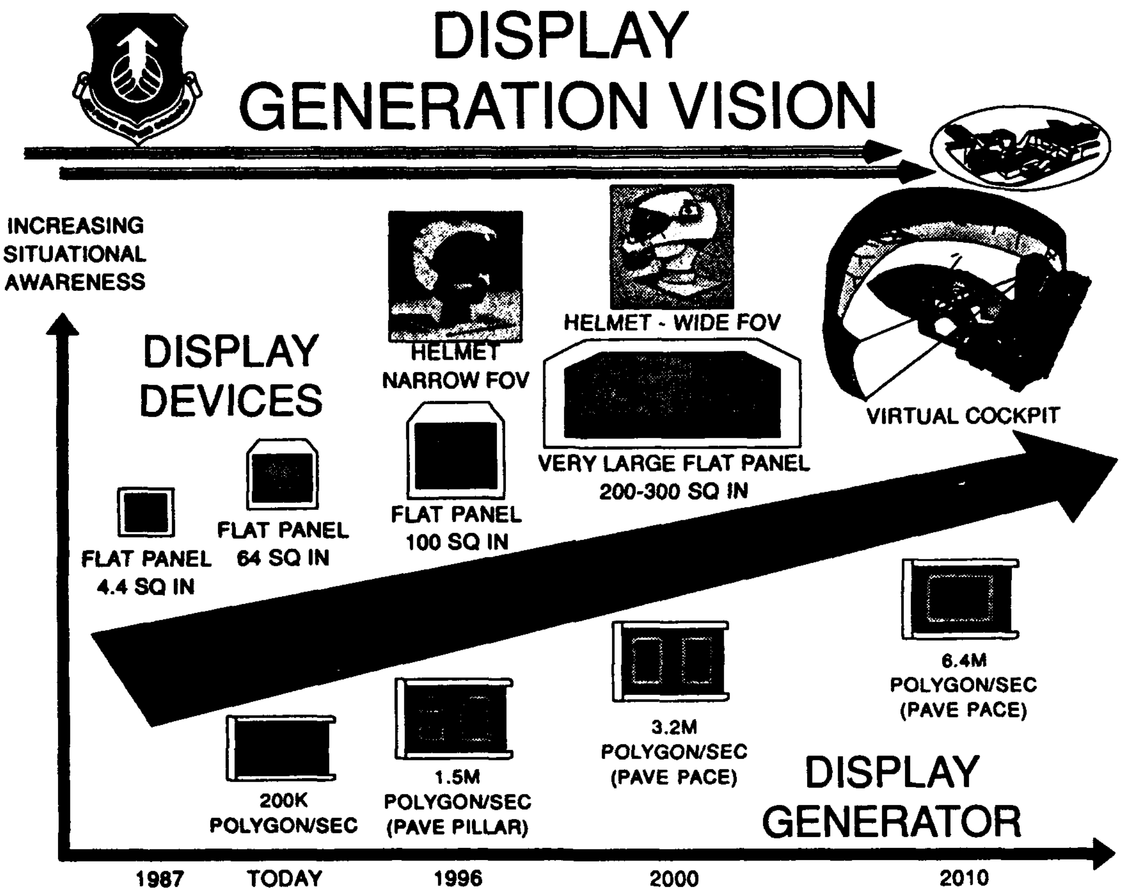

Figure 8. Display Technology Office vision for the evolution of displays and display generators.

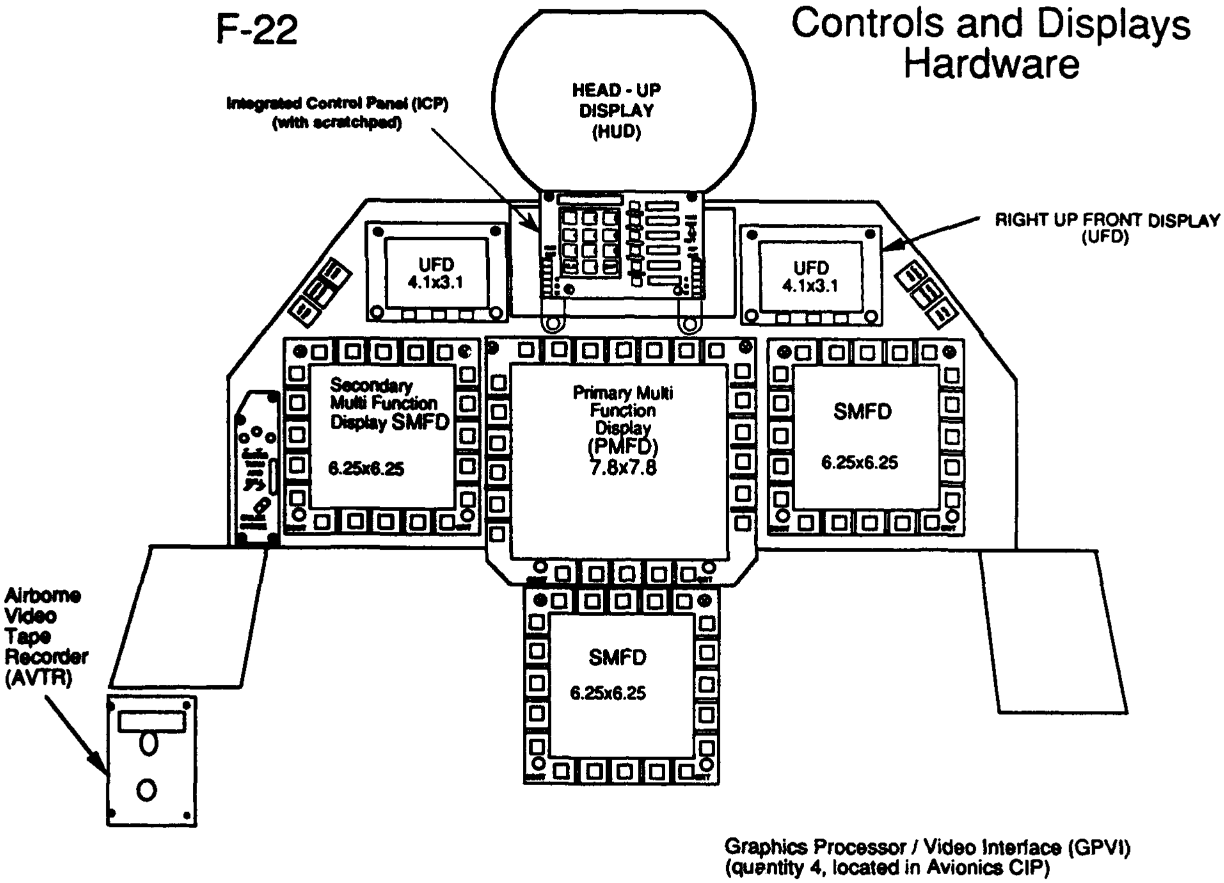

Figure 9. Schematic drawing of F-22 controls and displays for EMD.

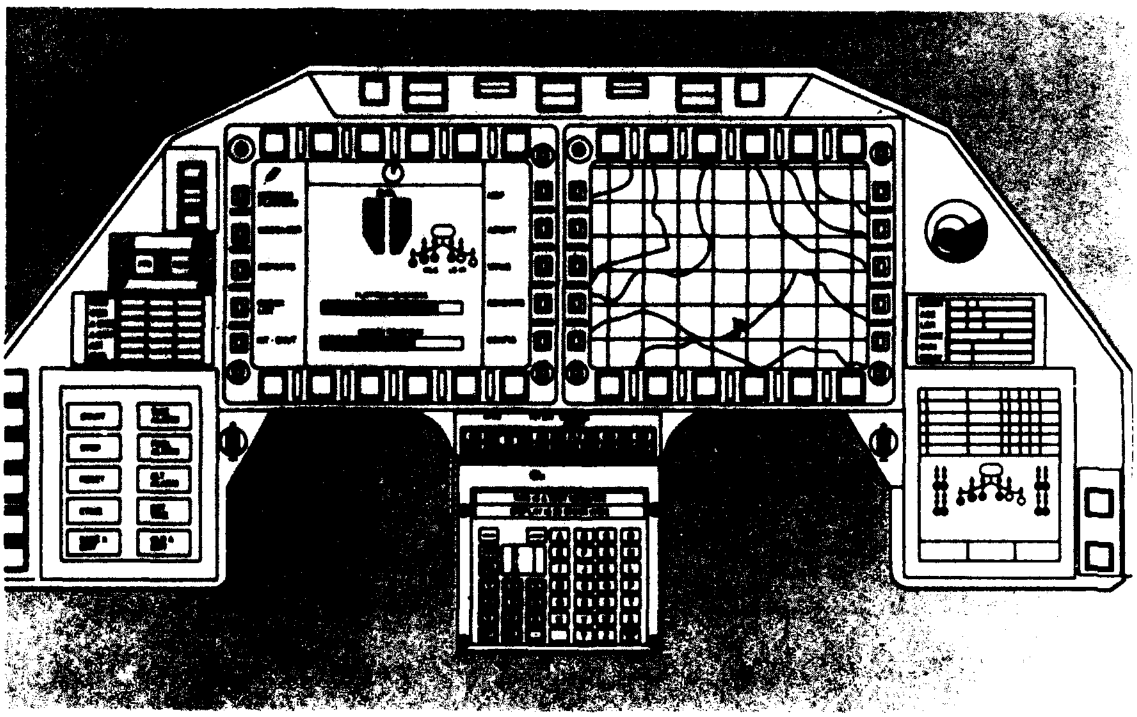

Figure 10. Schematic drawing of RAH-66 displays for EMD.

Figure 11. Photograph of C-130 RAMTIP cockpit displays.

Figure 12. Litton CdSe AMLCD used at navigator's station in RAMTIP with drivers and connectors shown.

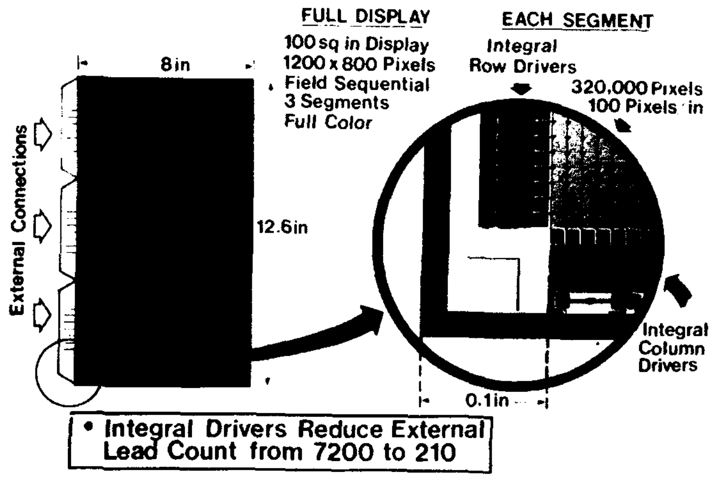

Figure 13. Butt-coupling of p-Si AMLCDs to create a large area display (CHDD program). Note: the lead count has been further reduced from 210 to 132.

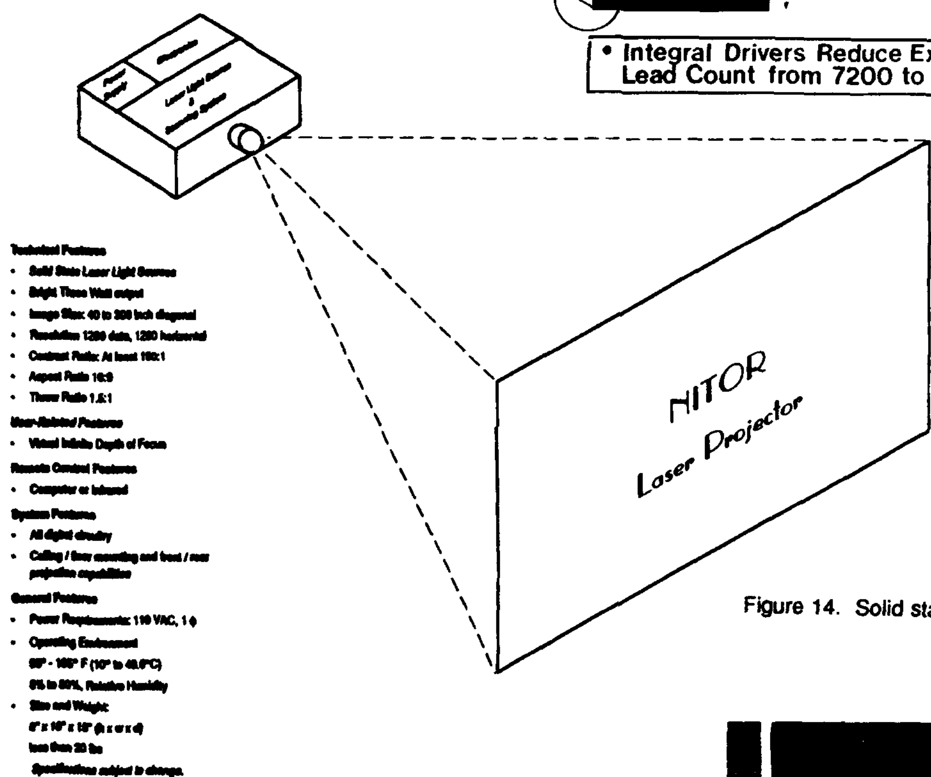

Figure 14. Solid state laser projector concept.

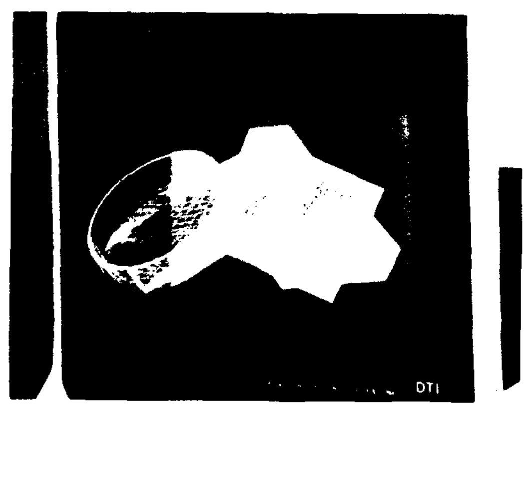

Figure 15. Autostereoscopic 3D display.

Discussion

QUESTION D.V. GAGGIN

Virtual Cockpits and Panoramic Displays are complementary techniques. Does the U S Air Force have a program that will bring these together in the near future?

REPLY

Yes. Panoramic Displays will be available to cockpit designers by the year 2000. Virtual Cockpits will be available by 2020. Both large-area aircraft-mounted and helmet-mounted display systems will have on the order of 3 million pixels for each eye. The graphics processor has yet to be developed, but will be similar for each of these types of display. Thus the development of panoramic aircraft-mounted displays is a pre-requisite to the development of virtual cockpits.

QUESTION O. FOURURE

The concepts of Panoramic Displays and Virtual Cockpits both aim at developing synthetic presentations to the pilot, with geographic, tactical and system status information, to improve situation awareness. Are these two concepts compatible with each other? What should be the priority in R&D in the near future?

REPLY

Concerning priority, panoramic displays for the year 2000 are the higher priority. Technology permits that realization 20 years earlier than the virtual cockpit.

Concerning compatibility, the two concepts are compatible in the sense that the development of the panoramic display technology will come first and help in the subsequent development of the virtual cockpit. Once enough elements of the Supercockpit concept (i.e.the virtual cockpit) have been developed, it will be possible for trade-off studies to be conducted between aircraft-mounted and helmet-mounted panoramic displays. This will occur in the period 2010 to 2020, in our estimation. Supercockpit requires at least 120 degees * 60 degrees high resolution video color from the display whether mounted on the aircraft or on the helmet. A 100% virtual cockpit, as described by Martin (Paper 8) would obviate the need for aircraft-mounted displays, provided the pilot would accept it, but we believe he will only do so for limited mission segments. The pilot will want to see through the helmet display and fly without it most of the time.

Additional Note: The Supercockpit requires a full-color stereo binocular helmet-mounted display having 2 - 4 million pixels per eye. Such displays do not currently exist. We are just beginning development of a 1 million pixel monochrome display, and it will be 10 years before a display of the full capability required will be available for research.

VOL AU-DESSUS D'UN MONDE VIRTUEL

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1. SOMMAIRE

La recherche de solutions "discrètes" pour les vols de pénétration à très basse altitude amène à considérer l'usage des fichiers de terrain, de plus en plus facilement disponibles.

Ces considérations ont conduit le Ministère Français de la Défense à confier à DASSAULT AVIATION une étude, dans le cadre du Développement Exploratoire APIS (Aide au Pilotage par Imagerie Synthétique), relative à l'utilisation de tels fichiers pour la constitution d'images de synthèse à bord des avions de combat. Ces images doivent servir à aider le pilote à conduire sa mission par tous les temps ou la nuit, en suppléant la vision directe du monde extérieur.

Cette recherche de concept a utilisé en particulier des outils de simulation pilotée temps réel qui ont permis de mettre au point différentes figurations APIS en tête haute et en tête moyenne.

Cette communication présente la démarche parcourue dans la mise au point de ces figurations avec la participation des Services Officiels et donne des exemples des propositions faites.

Ces images ont été évaluées par un groupe de dix pilotes comprenant aussi bien des pilotes d'essais que des pilotes des Forces. L'évaluation conduite par le CERMA a mis en évidence leur intérêt ergonomique.

Toutefois, de nombreux points demeurent à régler : la faisabilité technique dans des volumes et des coûts raisonnables, les aspects liés à la sécurité ou à la fiabilité de tels dispositifs...

2. SUMMARY

Research for stealth methods of low level penetration flight leads us to consider the use of terrain data bases which are becoming more and more easily available.

This is why the French Ministry of Defence has granted DASSAULT AVIATION a contract in the scope of the APIS[1] Exploratory Programme. The purpose of this study was to consider the use of terrain files for designing synthetic images intended for combat aircraft. The aim is to provide the pilot with pictures replacing direct sight on the outside world, thus helping him to conduct the flight by any weather or at night.

The research for this new concept was supported by intensive software development on real time simulation tools. The latter permitted the proposal of different APIS representations for both head-up and head-level displays.

This paper presents the process we followed during the elaboration of the images with the active participation of the French Officials. We also give some examples of proposed pictures.

At the end of the study these proposals were assessed by a team of ten military pilots, belonging either to flight test teams or coming from French Navy and Air Force. This evaluation has been carried out by the CERMA (French Aero-Medical Research Institute).

However, many points are still to be examined : how to display these pictures onboard while managing safety and limiting costs and resources consumption at an affordable level.

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[1] This French abbreviation means : Help to Pilot using Synthetic Imageries

3. ABREVIATIONS

APIS	Aide au Pilotage par Imagerie Synthétique
BPSA	Bureau des Programmes de Systèmes d'Armes (de l'EMAA)
CEAM	Centre d'Expérimentations Aériennes Militaires
CERMA	Centre d'Etudes et de Recherches de Médecine Aérospatiale
CEV	Centre d'Essais en Vol
CTH	Collimateur Tête Haute
CTM	Collimateur Tête Moyenne
DE	Développement Exploratoire
DGA	Délégation Générale à l'Armement (du Ministère de la Défense)
DGAC	Direction Générale de l'Aviation Civile
EMAA	Etat-Major de l'Armée de l'Air
HUD	Head-Up Display (terme anglais pour CTH)
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions (conditions de vol aux instruments)
LAMAS	Laboratoire de Médecine Aérospatiale (du CEV)
OASIS	Outil d'Aide à la Spécification des Informations Système
OPE	Organisation du Poste d'Equipage
PERSEPOLIS	Programme d'Etudes et de Réalisations d'un Système Electronique Pour l'Organisation et la Lecture d'Informations Synthétiques
STTE	Service Technique des Télécommunications et des Equipements aéronautiques
TBA	Très Basse Altitude

4. INTRODUCTION

Dans la conception de l'aviation de combat moderne, les appareils doivent posséder de nombreuses capacités et en tout premier lieu celles d'observer ou d'attaquer les positions de l'ennemi au sol quelquefois assez en arrière de la ligne des combats. Dans toutes les forces aériennes, ces missions sont différemment répertoriées mais on trouve en général les mêmes grands thèmes ; retenons en particulier l'attaque d'objectifs fixes de taille et de valeur importantes (usines, etc), la destruction de nœuds de communication (ouvrages d'art, tunnels...), la désorganisation des aérodromes (pistes, radars, éventuellement aéronefs au sol) ou encore la localisation et la neutralisation des défenses sol-air.

Pour toutes ces missions, un grand point commun : l'arrivée au voisinage de l'objectif ou du point de tir se fait en vol de pénétration à très basse altitude ("vol TBA"). Seul ce type de vol permet de traverser avec succès les défenses sol-air de l'adversaire. Selon les différents scénarios, cette phase de vol varie en durée et en tolérance sur les vitesses et hauteurs de vol à pratiquer.

La tendance générale des dernières années a été : plus vite, plus bas, plus longtemps. Ainsi, là où opéraient avant les MIRAGE III-E, doivent opérer maintenant des MIRAGE 2000-N, dotés d'un Système de Navigation et d'Armement offrant des modes de "suivi de terrain". Aujourd'hui, ces limites de vitesse et de hauteur étant sans cesse plus difficiles à repousser, on cherche à gagner en discrétion. C'est ainsi que le "suivi de terrain" à base de radar, classique pour un F 111 ou un TORNADO (IDS), doit évoluer. C'est ce qu'il a déjà fait dans les MIRAGE 2000-N et les tout derniers MIRAGE 2000-D où des capacités de "vol sur fichier" existent en complément aux modes utilisant le radar ANTILOPE.

Le "vol sur fichier" exploite toutes les possibilités des techniques modernes en matière de connaissance du relief. La constitution de bases de données de terrain en n'importe quelle région de la Terre est à notre portée grâce en particulier aux observations par satellite. Les progrès en matière de traitement de l'information au sol et aussi en vol permettent de stocker à bord de l'avion les zones que l'on se propose de survoler.

L'avènement de ces techniques a ainsi conduit le Ministère Français de la Défense à lancer un Développement Exploratoire sur ce thème. Dénommé APIS (pour Aide au Pilote par Imagerie Synthétique), il a pour objectif de mettre en place des concepts nouveaux où l'utilisation large de tels fichiers permettrait de conduire une partie importante de la mission, en particulier en vol TBA, dans des conditions de mauvaise visibilité (tout temps et/ou nuit) par le biais de présentation au pilote d'imageries synthétiques.

Dans un premier temps, les équipes de DASSAULT AVIATION ont été chargées d'établir les premières bases d'un tel concept.

5. LES ORIGINES

Avant de rentrer dans l'explication des principes retenus pour le concept APIS proposé, il est bon de revenir sur des études antérieures dans lesquelles on trouve les fondements de la démarche suivie pour APIS.

5.1 PERSEPOLIS et le pilotage tête haute

En France, dans les années 1970, un mouvement important s'est fait en faveur d'un principe nouveau de pilotage des aéronefs baptisé "pilotage tête haute". On pourra en trouver une bonne description dans les travaux de M. KLOPFSTEIN du CEV (voir notamment référence 1).

L'idée de base a eté de montrer à l'échelle 1, en superposition avec le monde extérieur le vecteur vitesse, l'horizon et l'échelle d'assiette.

Ce mouvement s'est fait grâce à un triple progrès technologique :

- l'apparition des premiers capteurs inertiels de précision et en particulier des centrales à inertie capables de fournir attitudes et vitesses avec des erreurs limitées ;
- le développement des calculateurs électroniques embarqués (début des techniques numériques) ;
- la mise au point de viseurs à tube cathodique, qui, bien que monochromes, permettaient d'afficher à la demande une grande variété de symboles graphiques ou alphanumériques avec des lois de présence-absence ou de déplacement très peu contraintes.

Ces derniers constituaient un progrès réel par rapport aux viseurs électro-mécaniques (à plaques et lampes) déjà présents dans les avions de combat pour les besoins de visée des conduites de tir. D'ailleurs l'aviation de combat de par le monde s'est très aisément convertie dans les années qui suivirent à l'utilisation de ces dispositifs tête haute pour le pilotage.

Plusieurs propositions ont été faites pour développer ces mêmes techniques sur avions civils. Déjà le MERCURE montrait la voie, avec un HUD à diodes et chez DASSAULT, à l'occasion d'un programme d'études désigné PERSEPOLIS, on a cherché comment aller au-delà de ces premiers développements du pilotage tête haute.

PERSEPOLIS a été mené en association avec THOMSON-CSF sur soutien de la DGA et de la DGAC. Son orientation majeure a été de retenir des principes visant à retrouver un pilotage naturel (utilisant la pente et la route), fondé sur la liaison avec le monde extérieur.

La figure 1 montre un cas typique de la symbologie PERSEPOLIS en approche. On note en particulier, en plus de l'horizon (repère 1) et du vecteur vitesse-sol (repère 3), l'indication de la pente potentielle (repère 6) et le tracé d'une piste synthétique (repère 8). Celle-ci est tracée à partir des indications données par l'ILS.

On se pose correctement en faisant coïncider la trajectoire (vecteur-vitesse) avec cette piste, comme on l'apprend en aéro-club lors des premières leçons de vol à vue. On peut être aidé en cela par deux réticules (voir repères 5 et 7) proposant un "guidage" relatif au vecteur vitesse et à la pente potentielle.

Ce sont des figurations de ce type qui sont opérationnelles sur les avions DASSAULT, en particulier pour le programme MIRAGE 2000, et maintenant sur le RAFALE.

Le principe "retour au naturel" dont témoigne cette démarche va dans la ligne de conduite prônée par l'approche "facteurs humains" : comprendre l'homme, chercher à utiliser au mieux ses compétences, son habileté, ses "automatismes".

Avant de quitter le monde des avions civils, on mentionnera qu'il existe de plus en plus d'avions civils dotés de viseurs électroniques permettant un certain pilotage tête haute et que le mouvement gagne lentement du terrain malgré le surcoût que cette option implique. Des HUD FLIGHT DYNAMICS ont été installés sur des B 727 ou le seront bientôt sur des B 737-400 et des MD-83. Et bien sûr, un HUD SEXTANT AVIONIQUE équipe tous les A 320 d'AIR INTER. Comme l'indique la FLIGHT SAFETY FOUNDATION (voir rapport cité en référence 2), cet investissement se révèle payant dans la sécurité du vol et son impact dans la relation homme-machine est très favorable, comme en témoignent les syndicats de pilotes (voir par exemple article cité en référence 3). Par ailleurs, son intégration à l'électronique de bord est un point d'étude d'architecture intéressant abordé dans la communication citée en référence 4.

5.2 L'étude O.P.E.

O.P.E. pour Organisation du Poste d'Equipage (d'un Avion de Combat) est le nom d'un autre Développement Exploratoire mené de 81 à 83 par DASSAULT avec le concours de THOMSON-CSF et SV2 (CROUZET-SFENA) sur soutien de la DGA (STTE). Son but était la définition d'une cabine d'avion d'armes à siège incliné, faisant appel aux technologies nouvelles

d'interface homme-machine. Le programme s'appuyait sur des maquettes et des essais en centrifugeuse du CEV/LAMAS (voir référence 5).

Plusieurs idées maîtresses ou concepts nouveaux sont issues de ce D.E. et ont été appliquées en grande partie sur l'Avion Expérimental RAFALE-A. Certains de ces principes ont aussi été repris pour le programme MIRAGE 2000-5.

Le pilotage tête haute étant toujours une des principales caractéristiques des cockpits modernes, l'O.P.E. a conduit à développer la technologie des viseurs "holographiques" (à optique diffractive). Ceux-ci procurent sur les viseurs classiques deux avantages de taille :
- le champ : 30° d'ouverture en gisement par 20° d'ouverture en site est un chiffre typique et on a même retenu plus sur RAFALE
- les performances photométriques : à double titre, le CTH en devenant très transparent n'altère que faiblement la vision de l'extérieur, et la symbologie est perçue dans toutes les conditions de vol (face au soleil, dos au soleil...).

Mais l'O.P.E. a proposé des concepts plus originaux, en particulier le principe du Collimateur Tête Moyenne (CTM) : toutes les informations à présenter au pilote n'ont pas besoin d'être présentées en tête haute, n'étant pas liées au monde extérieur (du moins à sa partie accessible en vision directe). Mais présentées dans un écran tête basse classique, elles peuvent se révéler difficiles d'accès par un coup d'œil rapide. On crée donc un terminal de visualisation, placé géométriquement très près du CTH (juste au-dessous) et procurant des images projetées à une distance équivalente à celles du viseur. Celles-ci sont donc rapidement accessibles. De plus, la collimation (projection à distance) les met à l'abri de bon nombre de reflets parasites.

Le premier CTM a volé sur l'Avion Expérimental RAFALE-A. Depuis, des équipements ont été fabriqués en série dans le cadre de la modernisation des SUPER-ETENDARD et pour le MIRAGE 2000-5. Ces équipements, monochromes, sont particulièrement bien placés pour la présentation des visualisations issues des capteurs (pods optroniques ou radars). Pour les RAFALE destinés à équiper la MARINE NATIONALE et L'ARMEE de L'AIR FRANCAISE, est développé par SEXTANT AVIONIQUE un CTM polychrome à grand champ (20° par 20°) qui servira à la fois pour les capteurs et aussi pour la représentation de la situation tactique. Ce projet est décrit dans la communication citée en référence 6.

En outre, un grand nombre de principes de réalisation dans les logiques de présentation ou de commande ont été proposés par le groupe O.P.E. Beaucoup de ceux-ci ont été expérimentés sur le RAFALE-A. Ils témoignent là encore tous d'un état d'esprit de simplicité et de naturel.

Prenons un exemple : on connaît classiquement dans les cabines la commande faisant passer une centrale à inertie de l'état "alignement" à l'état "navigation". Avant de quitter le parking, la consigne est basculer "d'alignement" à "navigation". Si cette manœuvre est oubliée et qu'on commence à rouler en "alignement", toute la procédure d'alignement est à reprendre... et de précieuses minutes sont perdues, ce qui peut être un gros handicap pour des décollages sur alerte. Dans l'O.P.E, on a tout simplement remplacé cette consigne par une astuce faisant passer le système en "navigation" au desserrement du frein de parc. Ce dispositif est de base sur RAFALE.

Les premières esquisses de terrain synthétique en tête haute et tête moyenne (voir figure 2) ont été élaborées dans le contexte de l'étude O.P.E.

6. METHODE DE TRAVAIL

L'étude APIS, conduite sur deux ans, a clairement été séparée en deux étapes majeures, chacune donnant lieu à plusieurs présentations aux Services Officiels.

6.1. Les images statiques

La première étape a permis l'analyse exhaustive d'un très grand nombre de solutions de représentations, sous forme d'images statiques, et s'est terminée par la réalisation de films d'animation. C'est ainsi qu'on a pu regarder en tête haute par exemple, ce que donnait, sur différents types de terrain (plat, vallonné, montagneux...) différents principes de représentation :
- carroyage fixe au sol
- carroyage attaché à l'avion
- transversales
- fuyantes
- lignes de crêtes
- nœuds

On a aussi regardé quels éléments il fallait ajouter au paysage ainsi construit pour aider à son interprétation. Un point très étudié a été celui des "arbres". Dans la perception naturelle, la vue des arbres au sol permet d'apprécier la hauteur de vol, beaucoup plus instinctivement qu'un compteur ou qu'une échelle. On a donc cherché à implanter dans ces paysages synthétiques des arbres de différentes formes et différentes hauteurs. L'implantation de ces

arbres a elle-même été étudiée : alignements, implantations aléatoires ou répartition régulière le long de la trajectoire...

Dans les images tête moyenne, c'est aussi l'utilisation de la couleur et des différentes échelles qui ont été des facteurs importants de paramétrage.

6.2. Les films d'animation

Les images de tête haute et de tête moyenne qui semblaient les plus efficaces ont donné lieu à la réalisation d'images animées. Ces images ont été obtenues en enregistrant sur un magnétoscope vue par vue les images calculées. Dans cette étape, le souci majeur n'était pas celui de la performance "temps réel". On a ainsi réussi à créer des films de relief synthétique sur des terrains existants en France. En utilisant en outre des trajectoires réelles sur ces terrains, ces films synthétiques ont pu être comparés à des vols réels faits en suivi de terrain par un MIRAGE 2000-N dont on avait enregistré la tête haute.

Ces réalisations ont permis d'orienter les premiers choix et d'amorcer la deuxième étape de l'étude.

6.3. Le travail en simulation

Cette phase a été conduite principalement au centre de simulation OASIS de DASSAULT AVIATION à Istres.

On est donc parti des propositions les plus probantes faites à l'étape précédente, avec cette fois, de base, la préoccupation du temps de calcul.

Des essais préalables avaient eu lieu, en parallèle du travail précédent sur les images fixes, pour faire des choix sur les architectures informatiques (matérielles et logicielles) à retenir dans l'objectif du temps réel. Ces choix ont été présentés par M. Roland MIGINIAC au congrès AGARD/FMP de Bruxelles en Octobre 1991 (voir référence 7).

6.4. La concertation avec les Services Officiels

La méthode de travail retenue permettait donc de passer en revue un grand nombre de cas par les différentes paramétrisations évoquées. Le contrôle de projet mis en place avec les Services Officiels a permis de fixer les choix grâce à de fréquentes rencontres avec le BPSA, le CERMA et le STTE. Ces présentations ont périodiquement ponctué les développements ; elles ont permis à chaque fois de dresser un état des lieux, de recentrer ou de ré-orienter les recherches et de repartir quelquefois dans de nouvelles directions. C'est ainsi par exemple qu'est née au cours d'une séance de travail avec les Services Officiels l'idée de la vidéo pleine CTH (HUD4).

7. LA CONSTRUCTION DU MONDE APIS

Conformément à l'esprit d'origine du concept, la volonté d'une représentation naturelle "instinctive" a orienté les premières études. Le point de départ était de représenter le monde environnant à l'échelle 1 dans le CTH, en superposition du terrain réel (lorsqu'il est visible) ou en remplacement (sinon).

En fait, cette idée est progressivement apparue limitée du fait de la relative faiblesse du champ CTH vis-à-vis de la reproduction des effets de vision périphérique. D'où aussi la recherche de présentations en planche de bord, ce qui permet de s'affranchir de l'échelle 1 et même de prendre du recul (ou de l'avance !) par rapport à la situation réelle.

7.1. APIS en tête haute

L'image synthétique dessinée dans le CTH doit respecter un certain nombre de règles élémentaires :
- discrétion de la symbologie du terrain par rapport aux réticules classiques du pilotage tête haute ;
- clarté et lisibilité de la présentation ;
- transparence de l'ensemble pour voir le paysage réel quand c'est possible. Ces considérations ont amené à imaginer différentes solutions qui ont suivi la filière images statiques, films d'animation et enfin simulation pour celles qui apparaissaient les plus prometteuses (HUD1, HUD2 & HUD3). L'image HUD4 a été adoptée au cours des travaux en simulation.

Dénomination	Type de représentation
HUD1	Lignes iso-distances
HUD2	Lignes de crête
HUD3	Carroyage géographique
HUD4	Vidéo pleine

La solution HUD2, très appréciée lors des présentations d'images statiques, a été écartée lors des essais en dynamique puis en simulation. En effet, les lignes de crête relient des points géographiques qui, pour une position d'observation donnée correspondent à un maximum local du site d'observation. Ainsi, leur présence et leur nombre dépend beaucoup du relief du terrain et surtout de l'altitude de l'avion et de ses évolutions. Les pilotes sont gênés du fait de leur densité constamment variable et plutôt imprévisible ainsi que par les évolutions du tracé en fonction de l'avancement de l'avion.

Les carroyages correspondent à la représentation du relief par le dessin d'une grille filaire à mailles carrées plaquée sur le sol. La solution HUD3 utilisant ces principes de carroyage, fixes au sol, a finalement été rejetée car elle introduisait une charge graphique trop importante, nuisible à la bonne vision des réticules classiques et du terrain réel, sans être plus évidente à interpréter que HUD1.

Le principe des images HUD1 est simple : à intervalles réguliers, on trace des lignes perpendiculaires à la route avion qui épousent le relief du terrain. C'est cette voie qui est apparue la plus intéressante. Les lignes iso-distantes permettent une interprétation facile du terrain environnant, tout en offrant une bonne lisibilité du reste de la symbologie.

On a pu encore faire progresser cette représentation en incorporant un certain nombre d'aménagements, tel que le paramétrage de la distance entre les lignes, réglable à la demande par une commande à la disposition du pilote ("taux de terrain"). Mais l'astuce la plus déterminante a été d'introduire un estompage progressif de la luminosité de ces lignes en fonction de leur distance à l'avion. Celui-ci a aussi été testé avec HUD2 et HUD3.

Cet estompage est intéressant à plusieurs titres :
- il permet de retrouver le phénomène naturel physique, qui est un des facteurs monoculaires influant dans la perception du relief (voir référence 8)
- il permet de lutter contre l'afflux de lumière provoqué par le tassement de lignes correspondant aux distances lointaines
- il permet d'amortir l'apparition brusque de lignes à l'horizon, liée à la taille de la zone de terrain numérique pris en compte pour le calcul de l'image.

Enfin, nous avons été amenés à considérer l'utilisation d'une image non plus filaire comme les précédentes mais générée de façon similaire aux images tête basse, sous forme de "vidéo pleine". Baptisé HUD4, ce type d'image est obtenu en générant en chaque pixel une teinte verte[2] plus ou moins lumineuse en fonction des ombres créées par le relief sur le terrain. En surimpression de cette image, qui pour certains ressemble beaucoup à une vidéo d'un capteur optronique, figurent toujours des réticules classiques de pilotage. La trajectoire peut aussi être représentée ; la solution la meilleure semblant être alors de la dessiner sous la forme d'un ruban "noir", c'est à dire en fait transparent.

Dans ce type d'image, la vision du monde extérieur par transparence est envisageable par un réglage approprié de la luminosité générale. D'ailleurs, cette image semble plus adaptée aux vols en ambiance crépusculaire qu'aux luminances élevées du fait des capacités des viseurs à générer de forts niveaux de lumière tout en assurant un balayage vidéo complet.

Pour toutes ces figurations tête haute, l'habillage de l'image APIS brute du terrain comprend :
- des symbologies de pilotage, reprises des symbologies classiques utilisées sur MIRAGE 2000 et RAFALE ; en complément certains essais de réticule ont été faits de type directeurs d'ordres pour aider à la reprise en main ; des précautions particulières ont été prises pour favoriser la lecture des réticules sur le fond d'image APIS.
- des indications relatives aux obstacles et à la trajectoire de référence ; cette trajectoire est celle que l'avion doit suivre, telle qu'elle résulte généralement de la préparation de mission.

Pour les évaluations pilotées, ce sont les figurations type HUD1 et HUD4 qui ont été retenues.

7.2. APIS en tête moyenne

De base, les images à générer en tête moyenne ont été conçues comme des images pleines, puisque il n'y avait plus à assurer de "transparence". Les technologies adoptées en planche de bord de nos avions étant toutes capables de produire de larges palettes de couleurs, nous sommes d'emblée partis sur la définition d'images statiques polychromes.

Très vite, il est apparu qu'il était intéressant de présenter des images représentant un champ plus important qu'en CTH. L'hypothèse nominale de l'utilisation d'un CTM polychrome de type RAFALE (de 20° par 20°) nous a tout d'abord fait envisager des images de format carré représentant, par exemple, des zones de 60° par 60°.

Mais ce CTM étant capable de gérer plusieurs images en multi-fenêtrage, il est aussi apparu intéressant d'adopter un format d'image de 10° de hauteur par 20° de largeur. En effet, les grandes ouvertures angulaires en site sur le terrain n'apportent pas beaucoup d'aide. Par contre, l'utilisation de l'autre moitié du CTM peut être laissée à d'autres fonctions (gestion du vol, situation tactique horizontale, conduites de tir...).

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[2] Etre monochrome permet la compatibilité avec les CTH multimodes existants

Le travail sur images statiques a également permis de définir une politique d'utilisation de la couleur. Après plusieurs tâtonnements, au codage hypsométrique[3] a été préféré le monochrome (souvent à base grise) dans le but de laisser libre l'utilisation des couleurs pour d'autres habillages soit de nature planimétrique (villes, fleuves, forêts, etc) soit de nature tactique (menaces, zones de responsabilité, autres avions, etc).

Mais il reste encore un grand degré de liberté : celui du point d'observation. Naturellement, on peut calculer l'image de la position présente, comme pour la tête haute. Toutefois, notre étude étant centrée sur le vol TBA, a été vite évoquée la possibilité de "prendre de la hauteur", ce qui permet en particulier d'éloigner l'horizon optique. Dans ce contexte, on a étudié une "image d'élévation", vue depuis un point d'observation suffisamment au-dessus de la position avion pour que le relief situé à moins d'une distance donnée (15 km, typiquement) ne soit pas caché par un masque de terrain.

Passé ce premier stade, on a aussi pensé à "prendre du recul", ce qui permet de mieux voir la situation de part et d'autre de l'avion, où peuvent se trouver des équipiers par exemple.

A l'inverse, on a aussi pensé à prendre de l'avance et ont été simulées des "vues d'anticipation", vues fixes ou recalculées en faisant bouger le point d'observation ou l'angle de vue selon les souhaits du pilote. L'idée était de visualiser ainsi l'arrivée sur un objectif ou un passage délicat de l'itinéraire, plusieurs minutes à l'avance, avec la possibilité de *zoomer*, de s'élever, de changer d'axe, etc. Toutefois, ces images ont ensuite été écartées car elles semblent relever plus de la préparation de mission que du vol TBA dans un avion monoplace.

C'est en fait l'addition de différents déplacements du point d'observation qui a abouti au meilleur compromis, avec la création de l'image "demi-dieu". Cette dénomination[4] a été adoptée car l'image représente un moyen terme entre la situation horizontale bidimensionnelle avec son habillage cartographique ("vue de Dieu" ou "God's eye") et la vue directe du cockpit. Dans la vue demi-dieu, on regarde le terrain environnant à partir d'une position reculée et élevée par rapport à la position réelle. Dans cette image, périodiquement recalculée, mais qui n'évolue ni en roulis ni en tangage est représentée la position réelle par une "maquette" de l'avion, dont les attitudes varient.

L'habillage le plus souvent retenu est constitué par :
- la trajectoire de référence de l'avion (même définition qu'en tête haute), plaquée au sol
- des éléments de planimétrie : forêts, villes, fleuves...
- des obstacles ou dangers divers (lignes haute-tension, e.g.)
- les menaces sol-air, pour lesquelles on a choisi de faire figurer en couleur rouge-orangé, des zones de danger ; celles-ci sont obtenues par projection au sol de l'intervisibilité entre la menace et l'avion à la hauteur de vol courante.

Comme évoqué pour la tête haute, on a également cherché à incorporer à ces images un estompage progressif de lumière qui se traduit ici par un effet de brume dans les lointains.

Après différents (et laborieux) réglages sur les différents paramètres en particulier de recul, d'élévation, de brume, etc, c'est ce type d'image qui a été présenté aux évaluations pilotées.

8. EVALUATION

A la fin de l'étude, l'organisation de l'évaluation APIS en simulation pilotée à OASIS a été préparée et définie avec le CERMA, puis approuvée dans son principe par les Services Officiels, qui ont désigné dix pilotes évaluateurs. Ceux-ci étaient aussi bien des pilotes d'essais que des pilotes des Forces.

8.1. Méthodes et scénarios

La charge globale de travail demandée à chaque pilote était importante pour :
- se familiariser avec la cabine RAFALE, ses commandes et l'environnement de simulation
- assimiler et évaluer les différentes figurations APIS en tête haute et en tête moyenne, sur trois zones de relief différents

Chaque évaluation a de ce fait été scindée en deux séances distinctes (de préparation, puis d'évaluation) séparées de quelques jours d'assimilation.

Comme il se doit, les pilotes évaluateurs n'avaient pas auparavant participé aux simulations APIS dans la phase d'étude et tous avaient une bonne expérience opérationnelle du vol TBA.

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[3] Codage pour lequel on utilise différentes couleurs selon l'altitude

[4] Clin d'œil à la mythologie grecque, alors que le nom APIS appartient à la mythologie égyptienne

Pour ces tests, la présentation des images APIS était disponible en tête haute et en tête moyenne. Le monde extérieur de simulation était cohérent avec l'image APIS en tête haute ; mais un décalage de position pouvait être introduit pour simuler une dérive lente de la localisation de l'avion.

La première séance a permis généralement de présenter le cadre des travaux, les différentes figurations étudiées en précisant les figurations à évaluer (HUD1, HUD4 et vue demi-dieu) avec leurs différentes options (arbres, obstacles, trajectoire, brume, etc). Ces démonstrations permettaient aussi de faire connaissance avec les différents terrains disponibles en simulation.

La deuxième séance, constituant l'évaluation proprement dite, se déroulait selon le programme suivant :
a)PHASE A : Trois passages successifs sur une zone accidentée permettent de voir :
- une version de référence sans image APIS,
- un parcours identique avec APIS en tête haute où le pilote peut régler à sa convenance le "taux de terrain" et le type de figuration (HUD1 ou HUD4) selon les conditions de visibilité ;
- un dernier parcours effectué avec HUD1 ou HUD4 et la vue demi-dieu en CTM, en conditions IMC totales. Les reprises en main du pilotage sont possibles pour s'écarter de la trajectoire de référence.
Les mêmes passages sont proposés ensuite sur un second terrain de relief différent.
b)PHASE B : Un troisième terrain est utilisé pour deux passages. Le mode de pilotage automatique est disponible mais des reprises en main sont nécessaires pour éviter des menaces ou des obstacles imprévus. Lors d'un arrêt inopiné de la simulation, on demande au pilote de se situer géographiquement.
c)PHASE C : Le pilote peut demander avec une totale liberté de choix (terrain, images, options...) de rejouer les différentes possibilités offertes.

8.2. Résultats
Les résultats de l'évaluation sont résumés dans le tableau présenté en figure 8. Globalement ces résultats sont encourageants et permettent de penser que le développement de telles figurations peut apporter un avantage au pilote opérationnel en mission de pénétration à très basse altitude. De nombreuses observations ont bien sûr été formulées qui permettront de préciser ou de reprendre certains points (voir paragraphe 9.1).

Il apparaît clairement du tableau que l'image APIS tête haute permet une aide dans la gestion de la trajectoire à court terme. Elle autorise une certaine reprise en main et surtout, elle permet une meilleure compréhension des actions des automatismes de gestion de la trajectoire. Les commentaires faits ont également permis de constater que l'image HUD4 a été jugée plus facile à interpréter que la symbologie HUD1.

En tête moyenne, APIS offre un support possible pour la situation tactique.

9. DISCUSSION

9.1. Corrections ou améliorations de simulation
Les figurations présentées ont bénéficié d'un grand nombre d'heures de travail, liées en particulier aux logiciels. Mais les matériels informatiques progressant sans cesse, on sait que la même étude, partant des mêmes bases, prendrait aujourd'hui un certain nombre d'orientations différentes touchant non aux principes du concept mais à certains choix de réalisation. Certains de ces choix, faits dans la quête de la performance temps réel, pourraient être revus, ce qui corrigerait des critiques adressées lors de l'évaluation. Par exemple, ceci concerne les trajectoires dont le calcul d'élimination des parties cachées est simpliste, ce qui met leur projection au sol quelquefois en conflit avec la représentation du terrain. Dans la même idée, l'économie d'un traitement de lissage (anti-aliasing) en tête haute, donne des images désagréables lors de virages dépassant 20 à 30 degrés d'inclinaison ; cette économie ne serait plus de mise avec un matériel de dernière génération.

9.2. Evolutions du concept
Les tout premiers essais de paysage synthétique avaient montré que la vision du paysage réduite au champ du viseur ne permettait pas d'espérer un pilotage manuel des images APIS. L'étude décrite ici s'est donc orientée vers un support au pilotage automatique avec des capacités de reprise en main

Après les évaluations, cette position apparaît un peu réductrice, certains évaluateurs étant d'avis qu'au prix d'améliorations de présentation qu'ils jugent simples, les images CTH pourraient permettre une plus grande capacité de pilotage manuel. Ceci toutefois, doit être examiné avec prudence, compte-tenu des risques inhérents aux erreurs de fichiers ou aux mauvaises localisations.

9.3. Embarquabilité
Des contraintes ont été prises de base dans l'étude (champ des collimateurs, en particulier) pour pouvoir envisager une application embarquée à moyen terme. Toutefois, pour faire des images animées avec une cadence

suffisante, il nous a fallu utiliser des moyens informatiques sol qu'il est encore un peu présomptueux de considérer embarquables avec des objectifs raisonnables de volume et de prix.

Mais la principale difficulté viendra des aspects liés à la sécurité du vol. Les erreurs faites lors de la constitution des fichiers ou lors de leurs manipulation, les obstacles apparus récemment, les décalages entre le fichier et la position réelle du fait d'une mauvaise localisation... sont autant de pièges pour le vol au moyen d'une technique de type APIS.

10. SUITES POTENTIELLES

C'est pourquoi, une des suites les plus intéressantes de l'étude est d'examiner le couplage de cette technique avec la détection du relief par des capteurs. C'est surtout avec des capteurs électro-optiques (caméra thermique, notamment) que ce couplage apparaît le plus porteur du fait de la complémentarité des deux moyens. Un contrat sur ce thème est en préparation, pour lequel seront utilisées les images prises lors de vols de la nacelle RUBIS de DASSAULT AVIATION sur MIRAGE 2000.

Le STTE a également prévu des essais en vol sur avion banc d'essai FALCON 20, équipé de terminaux de visualisation proches de ceux du RAFALE. Ces essais seront préparés par des campagnes de simulation au centre de simulation du CEV.

L'ensemble de ces travaux permettra d'affiner le concept en vue d'équiper par la suite des avions d'armes. L'application aux avions civils peut également être envisagée, en particulier pour l'aide au vol au voisinage du sol lors des opérations de décollage et atterrissage.

11. CONCLUSIONS

Une étude de deux ans a été menée par DASSAULT AVIATION sur la présentation d'images synthétiques représentant l'environnement d'un avion en pénétration TBA. Une phase de travail sur images statiques a permis de passer en revue de nombreuses propositions. Les plus pertinentes ont donné lieu à des films d'animation. Dans une deuxième phase, l'utilisation de moyens de simulation temps réel a autorisé la mise au point de représentations en tête haute et en tête moyenne Des pilotes ont pu évaluer ces représentations. Leurs avis, largement positifs, militent pour une poursuite des travaux sur ce thème. Ceux-ci doivent maintenant porter sur la question incontournable de la sécurité du vol qui peut être résolue en particulier en associant les fichiers de terrain aux informations fournies par des capteurs embarqués.

12. REMERCIEMENTS

Les auteurs tiennent ici à remercier :

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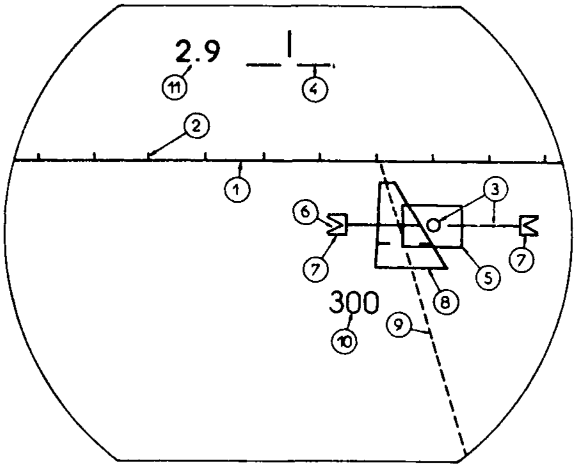

figure 1. PERSEPOLIS

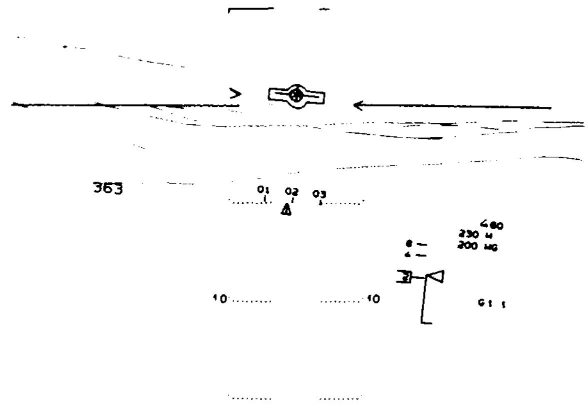

figure 4. APIS HUD2

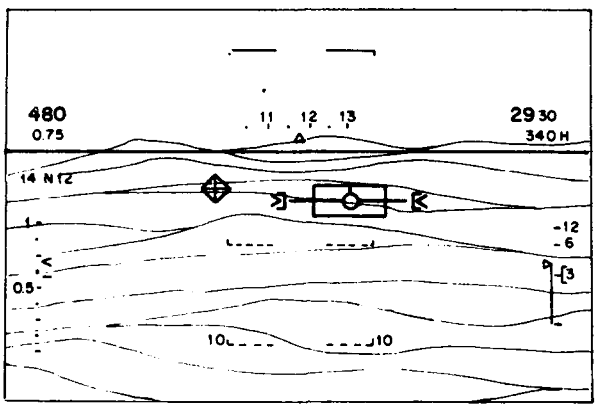

figure 2. O.P.E.

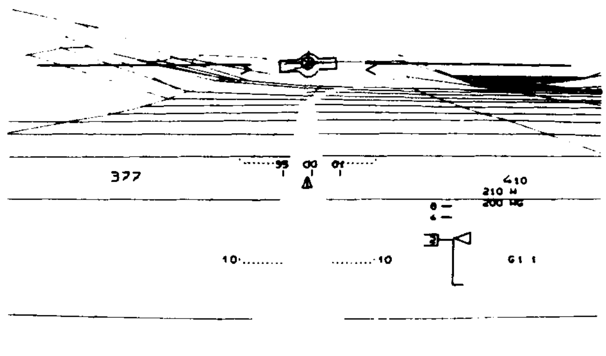

figure 5. APIS HUD3

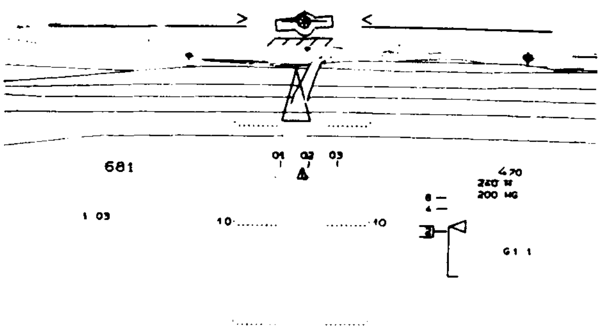

figure 3. APIS HUD1

figure 6. APIS HUD4

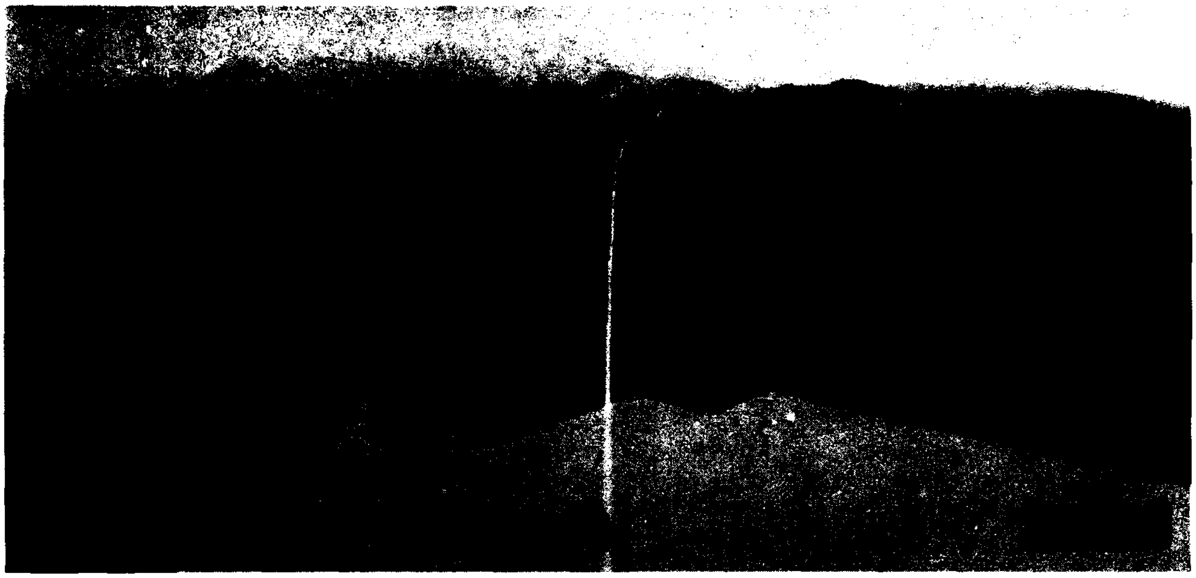

figure 7. APIS Vue demi-dieu

N.B. : La qualité des photographies et de la reproduction ne peut pas rendre l'impression des images APIS obtenues sur les écrans de visualisation (dynamique de lumière, ombrages, contrastes...)

EVALUATION APIS EN TETE HAUTE PAR 10 PILOTES MILITAIRES			
Utilisation fonctionnelle	**Rôle essentiel**	**Utile**	**Sans intérêt**
Compréhension de la situation instantanée	10	0	0
Anticipation des actions du pilotage automatique	5	3	2
Pilotage manuel	1	5	4

EVALUATION APIS EN TETE MOYENNE PAR 10 PILOTES MILITAIRES			
Utilisation fonctionnelle	**Rôle essentiel**	**Utile**	**Sans intérêt**
Compréhension de la situation court/moyen terme	5	5	0
Anticipation des actions du pilotage automatique	2	4	4
Pilotage manuel	3	3	4
Compréhension de la situation tactique	5	5	0

figure 8. Tableau de synthèse des évaluations

A NEW CONCEPT FOR HELMET MOUNTED VISION.

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1. SUMMARY.

Successful applications of holographic optical elements (HOEs) in the holographic night vision goggles have led to interesting developments of new concepts for helmet mounted vision systems.

The present application of HOEs in night vision goggles is discussed, as well as a new concept of Helmet Mounted Vision Systems.

2. INTRODUCTION.

Holographic Optical Elements (HOEs) have found applications in night vision goggles and helmet mounted night vision systems as a consequence of following important advantages.

HOEs can be made highly reflective for the light emerging from the I^2T (image intensifier tube) without significantly decreasing the light transmission from the outside world.

HOEs can perform optical functions which cannot be obtained with classical optical components.

The optical function of the HOE can be made independent of the shape of the substrate on which it is manufactured.

HOEs can be manufactured on various substrate materials (glass- plastics). The weight and the safety of night vision systems can be improved by the use of plastics instead of glass substrate materials.

In the following the advantages of the use of holographic optics are demonstrated in the existing holographic night vision goggles, and future developments of helmet mounted systems based on a holographic visor are discussed.

3. USE OF HOEs IN THE HOLOGRAPHIC NIGHT VISION GOGGLES.

3.1. Working principle.

The working principle of the night vision goggles (HNVG) is shown in fig. 1.

The image of the environment is projected onto the entrance plane of the I^2T by the objective. The amplified image is projected to the users eyes by the relay optics, the flat and the curved HOEs.

The HOEs have a dual function. The optical rays are deflected to the users eyes, and the HOEs perform the same function as a eye piece (a virtual image is formed at a large distance in front of the eyes).

The image intensifier tube (I^2T) contains a phosphor with a small bandwidth. The HOEs only have to reflect the light centralised around the peak wavelength of the phosphor (543nm) and can have a small spectral bandwidth. A typical spectral curve of both types of HOEs, recorded in DCG (dichromated gelatin), is shown in fig.2. The lower efficiency of the flat HOE for p- polarised light is caused by polarisation effects at the large angle of incidence (53°).

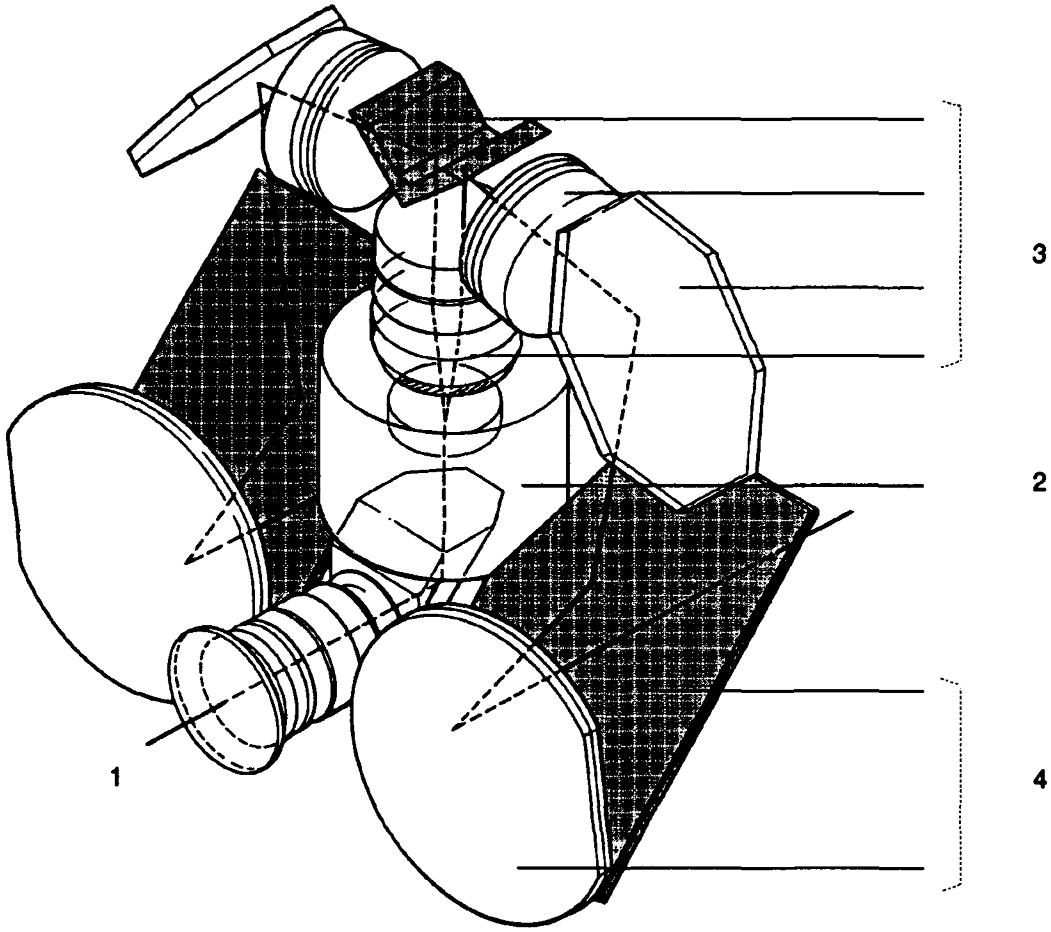

Fig. 1 : Working principle of the HNVG

Main elements are :

1 - the objective

2 - the I^2T

3 - the relay optics : collimator, roof mirror, relay lenses, mirror

4 - curved and flat HOEs

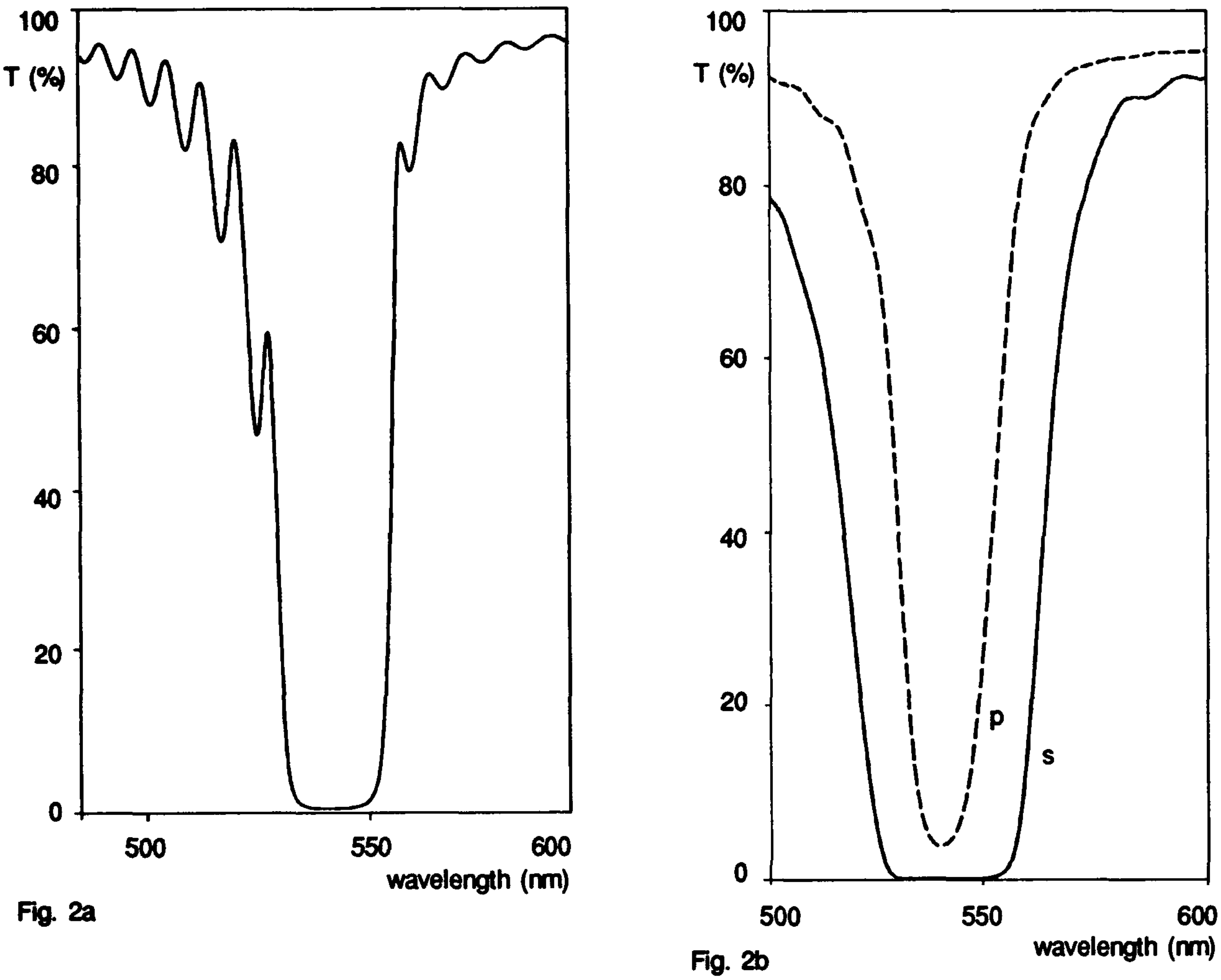

Fig. 2 : Transmission of the HOEs as a function of the wavelength
2a : curved HOE, angle of incidence 8°, unpolarized light
2b : flat HOE, angle of incidence 53°, s and p polarized light

The HOEs have to be made in such a way that all the rays generated by the I^2T and going through the optical system are reflected to the users eyes with the same high efficiency. To guarantee an almost constant diffraction efficiency over the total field of view, a point source located at the centre of the exit pupil of the optical system is used to record the HOEs. During replay, all field rays arriving at this exit pupil position are reflected with the same high efficiency.

To obtain a high diffraction efficiency at other pupil positions as well, the HOEs need to have a finite angular and wavelength bandwidth. Light rays arriving at the edges of the exit pupil are diffracted by the HOEs at a different angle than rays arriving at the centre. A change of the angle of incidence corresponds, according to the Bragg equation, to a change of the reconstruction wavelength. This wavelength shift is especially important for the flat HOEs:

The relation between the angle of incidence at a HOE and the peak reconstruction wavelength can be derived by differentiating the Bragg condition ref. [1] :

$$\frac{d\theta}{d\lambda} = \frac{K}{4\pi n}\sin(\phi - \theta) \qquad (1)$$

with : θ = the angle of incidence in DCG
ϕ = the angle between the grating vector and the normal to the HOE substrate (= 90°, conformal HOE case)
K = the grating vector
n = the index of refraction of DCG
λ = the peak reconstruction wavelength

At small angles of incidence (<10°, curved HOEs) a change of the angle of incidence at the HOE hardly influences the peak reconstruction wavelength. But at large angles of incidence (53°

for the central rays of the flat hologram, fig.3) a small change of the angle of incidence shifts the peak wavelength significantly. At a given location at the HOE, the difference between the angle of incidence of rays diffracted to the centre of the exit pupil and to the edges is about 6°. To guarantee efficient reflection of all the rays generated by the I²T and going through the optical system, the bandwidth of the flat HOE has to be at least 32 nm.

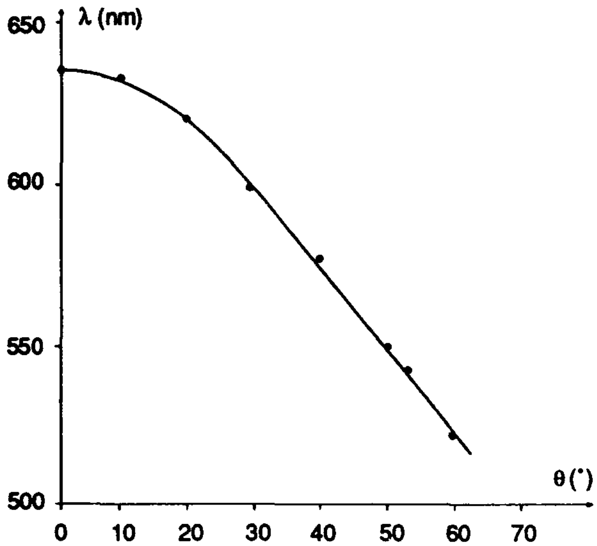

Fig. 3 : Relation between the reconstruction wavelength and the angle of incidence. This relation is derived form the Bragg equation. The HOE is designed to diffract rays at 53° angle of incidence, and wavelength 543nm.

The HOEs are thermally tuned and stabilised at the peak wavelength of the I²T and sealed between two glass substrates.

3.2. Photopic transmission.

The see through capability of the HOEs can be calculated in the following way:
Environmental light enters the flat HOE at an angle of incidence which is different from the angle of incidence of the night image rays. Therefore, according to the Bragg equation, the spectral curve of the flat HOE is shifted, as shown in fig.4. To calculate the photopic transmission, the wavelength dependence of the eye sensitivity has to be taken into account. The photopic transmission of the HOEs is obtained by multiplying the transmission of the HOEs with the eye sensitivity curves. The photopic transmission is higher than 40 %; a slightly pink discoloration of the outside world is observable.

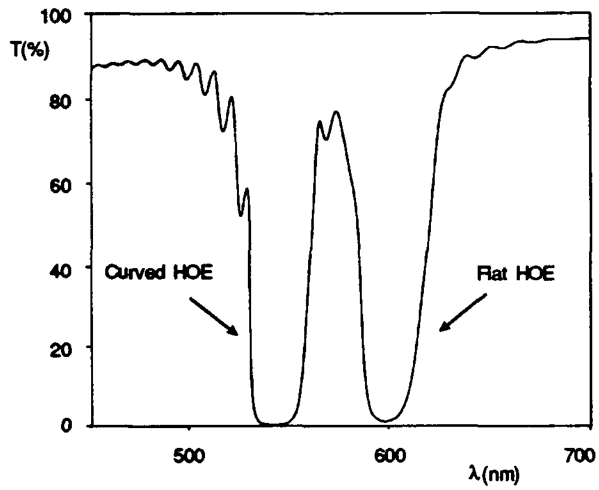

Fig. 4: Transmission of environmental light rays through the curved and the flat HOE. The reconstruction wavelength of the flat HOE is shifted to higher wavelengths, the environmental rays enter at the HOE at a smaller angle of incidence than the night image rays.

The advantage of the use of HOEs in front of the users eyes is obvious: The user never looses the image of the outside world, even when a sudden intens illumination of the environment takes place.

3.3. Future developments on the holographic night vision goggles.

Following improvements may be applied to the existing HNVG:

A first improvement can be obtained by manufacturing the HOEs on the plastic housing of the HNVG (polycarbonate visor and backplate). Since the radius of curvature, position and angular orientation of the visor is different from the curved glass substrates, a slight redesign of the optical system is necessary. Furthermore, problems with the use of plastics, which are discussed in more detail in the next paragraph, have to be taken into account.

A second improvement can be obtained by replacing the curved and flat HOE by one hologram. By this way the weight of the optical system is decreased and the discoloration of the outside world is further reduced.

4. DEVELOPMENTS OF A NEW CONCEPT OF THE HELMET MOUNTED VISION SYSTEMS.

4.1. Operational requirements.

The progress of the technology used in the holographic night vision goggles can result in the realization of a Helmet Mounted Vision System (HMVS) with a holographic visor for a pilot in a helicopter or fixed wing aircraft.

The operational requirements for such a HMVS can be summarized as follows:

- Optimization for the following tasks: Air-fight, air-attack, air-defence, tactical air-reconnaissance, support of other air-operations.

- Safety and environmental requirements similar to those for a conventional pilot helmet.

- A display of symbology and night vision images with sufficient brightness and quality, superimposed on the pilot's view of the outside world.

- Preferably protection against laser radiation and nuclear flashes.

- Center of gravity and weight compatible with human factor requirements, in particular in high-g conditions for fixed wing applications.

- Adequate life support and communication system.

- Accurate head position sensor system.

From the technical point of view the realization of a HMVS which complies with the above mentioned requirements is non-trivial, in particular with regard to weight, image quality and safety. A system concept will be discussed in the next

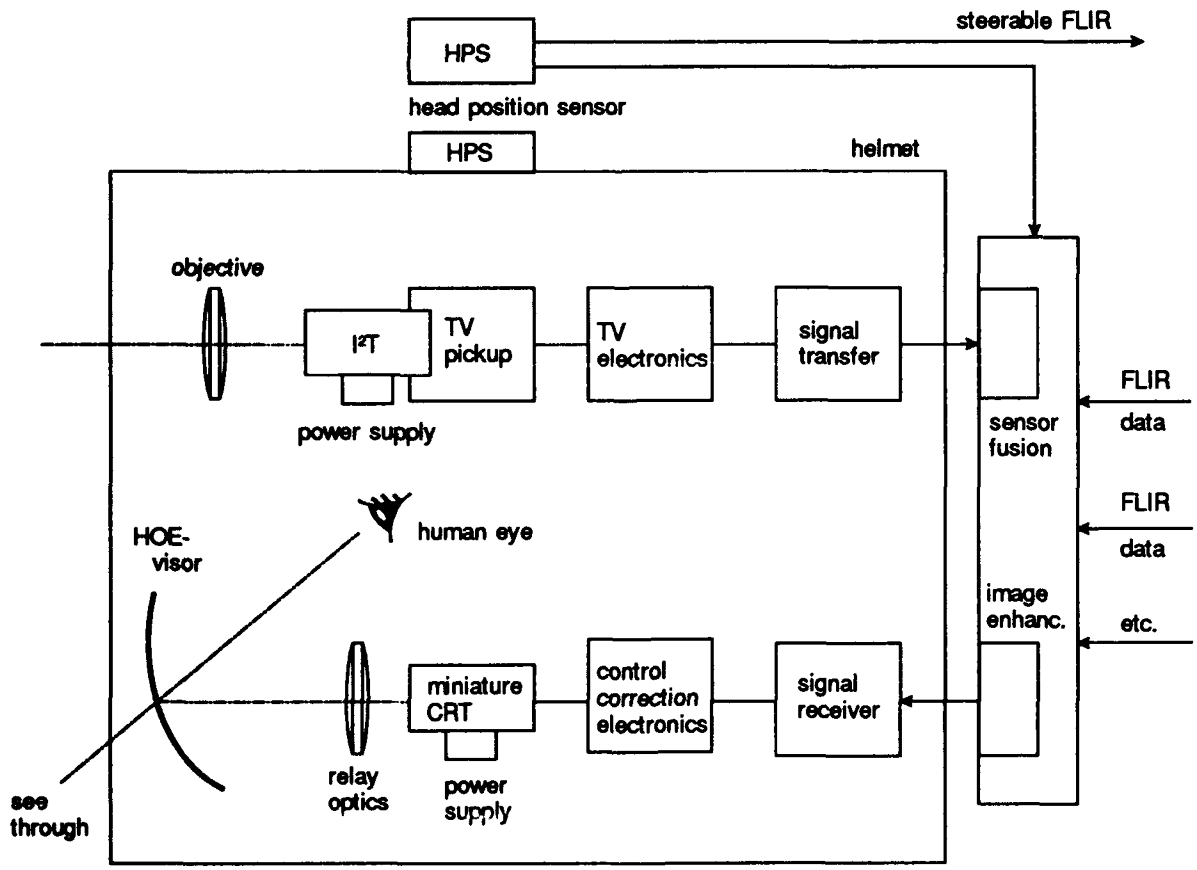

Fig. 5 : Basic concept of an integrated night vision helmet (HMVS)

sections, where emphasis is given to a new type of display subsystem,which is one of the key elements of the concept.

Present display-subsystems are characterized by limitations in peripheral view and/or field of view, transmission, weight and safety. The use of a subsystem based on a holographic visor, will significantly diminish these limitations.

4.2. System concept.

A basic concept of an integrated night vision helmet (Helmet Mounted Vision System, HMVS) is shown in fig. 5.
The system basically consists of a helmet with either bi-ocular or monocular display system:

- Display subsystem consisting of: CRT, Relay optics, Holographic visor
- Low Light Level Television Sensor (inside or outside helmet)
- Head position sensor
- Communication system

The concept has a high degree of flexibility.

Outside the helmet, flight data can be combined with FLIR (Forward Looking Infrared = Thermal Infrared) and/or LLLTV images, resulting in a (processed) video signal that is presented to a miniature CRT.
The CRT image is presented to the pilot by an optical relay system and holographic visor. The result is, that for the pilot, the CRT image is superimposed on the image of the outside world that is transmitted by the visor.
Whereas several helmet concepts show optical parts between the pilot's eyes and the visor (ref. [2], [3]), our concept is free of any optical element between the front head and the holographic visor ref. [4].

Nowadays, apart from the HOE visor concept, two other categories of display subsystems concepts can be distinguished:
- Concepts with combiner display optics between the pilot's eye(s) and the visor.
- Concepts with a visor that acts as a small bandwidth mirror for the CRT image projected by relay optics.

The advantages of the HOE concept as compared to the other two types are shown in table 1.

Type.	**Main feature of non-holographic concept.**	**Advantage of HMVS holographic display concept.**
Combiner display.	Optical elements in front of the eye.	No optical elements in front of the eye, no safety risks. A better eye relief. Lower weight.
Conventional visor projection.	Non-holographic visor, no optical elements in front of the eye.	Better reflection and transmission of the visor. Larger field of view.

Table 1 : Advantages of the holographic display concept as compared to conventional visor projection systems and systems with optical elements between the visor and the eyes.

4.3. Holographic visor concept.

In looking for a possibility to integrate a optical projection system (projection of a night image and/ or symbology) in the helmet of a pilot, without the need to insert optical components in front of the pilots eyes, integration of an holographic optical element in the visor of the helmet is a possible solution. During the design of the system difficulties arising from the optical function of the HOE and from the material properties of the polycarbonate visor have to be taken into account.

4.3.1. *Optical function of the HOE.*

During the design of the optical system one has to aim at a symmetrical HOE configuration. In such a system the angle of incidence at the HOE is equal to the angle of diffraction, or the HOE acts like a mirror. Furthermore, one has to aim at an off axis angle which is as small as possible for following reasons.

During recording of a HOE, a periodic modulation of the index of refraction is created. Surfaces of equal index, called fringe planes, are formed. If the HOE is used in a symmetrical configuration, the fringe planes are parallel to the hologram surface. In asymmetric HOEs, or HOEs with slanted fringes, the fringe planes intercept the HOE surface. As follows from the grating equation, asymmetric HOEs suffer from a large amount of chromatic aberrations, even when a phosphor with a narrow bandwidth is used.
The variation of the angle of diffraction i' with the wavelength λ , or the chromatic aberration of a reflection hologram, is calculated from the grating equation:

$$K = \frac{\lambda}{\sin i(\lambda) + \sin i'(\lambda)} \qquad (2)$$

with : i = the angle of incidence
i'= the angle of diffraction
K = a constant
λ = the wavelength

The difference between the angle of diffraction at two different wavelengths λ_0 and λ_1 at the same angle of incidence i, or the dispersion of the HOE, is calculated from :

$$\sin i'(\lambda_1) = \frac{\lambda_1 \sin i'(\lambda_0) + (\lambda_1 - \lambda_0) \sin i}{\lambda_0} \qquad (3)$$

The HOE is free from dispersion if $i'(\lambda_0) = i'(\lambda_1)$.
This condition is fulfilled if $i'(\lambda_0) = -i$, or if the HOE is symmetrical.

Monochromatic aberrations, appearing if the light enters the hologram during replay in a different way as during recording, also increase dramatically if the HOE is used in a asymmetrical configuration. These aberrations are also strongly dependent on the off- axis angle at which the HOE is used.

Another problem related to HOEs with slanted fringes, is called flare. At the HOE surface, modulations in the index of refraction of DCG and/ or modulations in the thickness of the holographic emulsion by swelling or shrinkage after exposure can create a thin transmission hologram. Diffraction of bright objects by this extra transmission hologram, generating spurious rainbow patterns, can be very disturbing for the pilot.

4.3.2. *Material properties of polycarbonate.*

Other difficulties related to the integration of a HOE in the visor of a helmet are caused by the material properties of the polycarbonate visor itself. A first problem is related to sealing of the HOE against humidity. Polycarbonate is not waterproof and HOEs in DCG are not resistant to humidity. If humidity reaches the hologram, the peak reconstruction wavelength i.e. the wavelength for which the Bragg condition is fulfilled at a given angle of incidence, shifts to higher values and the diffraction efficiency decreases. Therefore, special sealing precautions have to be taken to prevent humidity to reach the hologram.

A further problem is generated by internal stresses in the polycarbonate visor, which introduce optical birefringence. Optical birefringence can cause inhomogeneities in the diffraction efficiency. This problem is discussed in detail in ref. [5]

4.3.3. *Optical concept.*

As mentioned in paragraph 4.3.1., during the design of the optical system one has to aim at a minimum deviation of the symmetrical function of the visor HOEs.

The HOEs on the visor have to perform a dual function (fig.5). Rays from the relay optics have to be deflected to the pilots eyes, and the HOEs have to perform the same function as a eye piece.

To meet the above mentioned requirements, one has to ensure that the difference between the angle of incidence and diffraction at the HOE is as small as possible.
In the configuration shown in fig.6, a large asymmetry is introduced at the HOE in front of the eye. Incident and diffracted rays even lie at the same side of the normal. Large chromatic and monochromatic aberrations have to be corrected for.

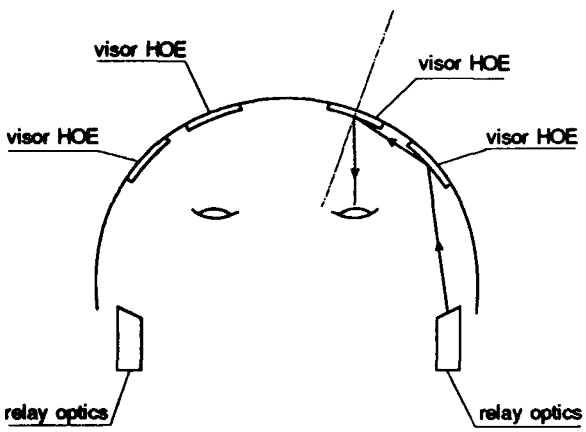

Fig. 6 : Optical concept : Integration of an holographic element in the visor. Note the large asymmetry of the visor hologram in front of the eye.

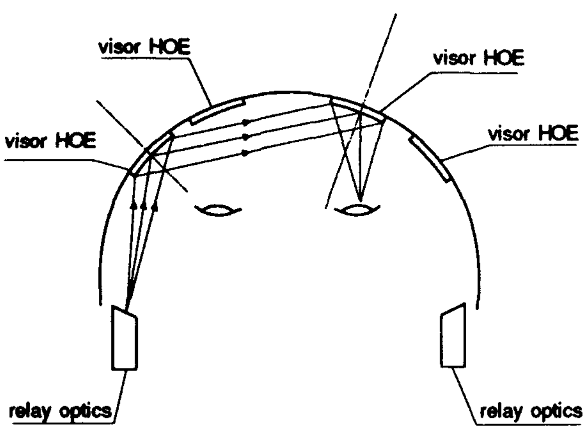

Fig. 7 : Optical concept : Integration of an holographic element in the visor. Projection to the opposite eye reduces the HOE asymmetry.

A more favourable situation is obtained if the rays from the relay optics are projected to the opposite eye by means of two HOEs on the visor (fig.7). This idea is described in ref.[4]. The asymmetry at the visor HOEs is highly reduced, and corrections of chromatic and monochromatic aberrations are much smaller. Aberrations originating from the large off- angles still have to be corrected in the relay optics and in the recording configuration of the HOEs.

4.4. Image intensifier imaging sensors and display aspects.

The HMVS with its holographic visor is in principle a light-weight and flight-safe, multi-purpose display device. Information from different imaging devices (either used separately or by combination through image fusion) such as Image Intensifiers, FLIR or Radar Imagers can be combined with all types of flight information data.

For a fully integrated HMVS only a Image Intensifier coupled directly to a Low Light Level TeleVision system, (LLLTV) can be used as an on-helmet imaging device.
The LLLTV, or also called the Intensified CCD camera, gives the advantages of low-weight, minimum parallax and direct Line of Sight control by movements of the head.
This LLLTV concept is described in more detail in ref. [6].

In this kind of systems, the weight, the dynamic range and the resolution are crucial aspects.

For the LLLTV system weight can be minimized by using plastic optics, a highly integrated design for I^2T tube and High Voltage Power Supply (HVPS) and finally by using electron-bombarded CCD's. The latter combination leaves out the anode screen and tapered fiber optics for coupling the I^2T tube with the CCD sensor.
In this way the additional weight for a LLLTV sensor can be reduced to approximately 170 grams.
Naturally the LLLTV sensor can be easily installed in other places within the airframe due to the fact that the image is available as a video-signal.
As compared with NVG's, LLLTV gives the main advantages of weight reduction (less optics required), optimization of center of gravity and flight-safety, and possibilities for image processing and sensor fusion.

A potential problem with using LLLTV sensors under several conditions of illuminance lies in both the overall dynamic range (more than a factor of 1000 between starlight and deep twilight) and the intrascene dynamic range, which can reach

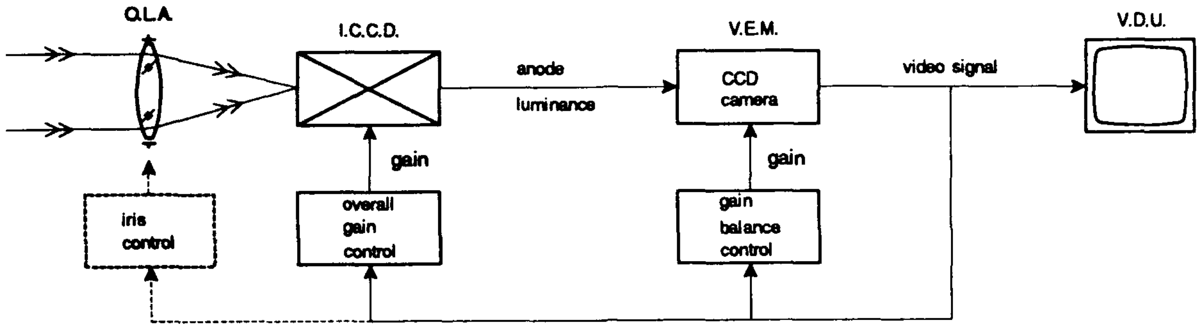

Fig. 8 : Diagram of adaptive LLLTV System [ref. 6]

values up to 100.000 between shadows and bright spots.

By using a highly sensitive I²T with carefully selected non linear characteristics and adaptive control mechanism, a separate control of I²T and CCD gain, and an analysis of the video-output for each pixel (see fig. 8 and ref. [6]), these problems will be minimized.
A further upward extension in overall dynamic range can be reached by using an auto-iris control mechanism or by implementation of cathode gating.

Resolution in combination with the required field of view (at least 40° diagonal) is not limited by the LLLTV system but by the video standards in combination with the use of CRT's.
A 1" miniaturized CRT (weight approximately 90 grams) is capable of displaying an extended CCIR video signal (576 vert. x 768 horizontal pixels) with sufficient brightness. Further miniaturization is highly unlikely due to physical restrictions. The additional weight for a dual on-helmet CRT system (which has several advantages as described below) with a combined HVPS unit will add up to approximately 300 grams.

High Definition TeleVision (HDTV) application however will require larger and thus heavier CRT's, which also has its implications on the HVPS for these components and on thermal dissipation. Therefore one must very carefully consider the actual operational requirement for system resolution.
The use of dual CRT system is preferable, even if only one imaging sensor is used, in order to have a potential solution for both the problems of dark-adaptation and binocular rivalry (ref. [7]).

A possible solution for the weight-problem in this case lies in the use of Fiber Optics coupling between the CRT and its related electronics (off-helmet) and relay optics (on-helmet).

5. CONCLUSION.

New developments in holographic night vision systems are described, with emphasis on the holographic visor concept. Integration of a HOE in the visor of the helmet improves the weight and the safety of the system, but limitations inherently related with the optical function of the HOEs and the material properties of the visor have to be taken into account during the design of HMVS.

A new concept for helmet mounted vision is described. This concept has a high degree of flexibility by the use of a LLLTV camera. Attention to the critical factors like weight, dynamic range and resolution is given.

6. ACKNOWLEDGEMENTS.

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We also thank the Royal Dutch Airforce, NLR, NLRGC, TNO-IZF and TNO-TPD for valuable support, discussions and contributions.

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UN VISUEL DE CASQUE POUR LE PILOTAGE ET LA NAVIGATION JOUR/NUIT DES AERONEFS DE COMBAT : Exigences et approche technique

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0 RESUME

Les exigences de pilotage et de navigation de jour comme de nuit d'un aéronef de combat, contraignent l'interface homme-machine à une évolution permanente. Les quinze dernières années ont vu les collimateurs "tête haute" se généraliser sur les avions de combat. Cependant, malgré les techniques holographiques permettant d'augmenter la taille du champ optique présenté, la recherche portant sur l'amélioration du système d'armes est passée par la création d'une nouvelle interface appelée "Viseur de casque" placée devant l'oeil du pilote.
Cette interface permet au pilote de pointer les capteurs du système d'armes dans une direction donnée, et, inversement au Système de navigation et d'armement, de montrer un objectif. La taille des champs optiques proposés pour les viseurs de casque, équivalente au champ d'un viseur tête haute classique, reste insuffisante pour autoriser le pilotage ou la navigation en toute sécurité. Tout au plus quelques paramètres peuvent-ils être présentés pour aider le pilote dans la réalisation de sa mission.
Les techniques s'améliorant, l'existence de ce type d'interface a donné la possibilité de présenter une image plus complexe devant les yeux du pilote. Il s'agit du "Visuel de Casque".
Un exposé des exigences de pilotage et de navigation en toutes conditions mettra en évidence les critères indispensables pris en compte pour la conception de ces nouveaux visuels.

1 INTRODUCTION

Les avions de combat modernes, confrontés à des menaces accrues doivent accomplir leurs missions de nuit comme de jour par toutes conditions météo. Pour la réussite de ces missions, ils disposent de capacités d'évolution accrues, d'armements évolués, et de capteurs nouveaux ou à capacités améliorées.

Il convient donc de les rendre capables de tirer pleinement bénéfice de ces moyens en réduisant globalement les délais d'exploitation et en assurant une couverture plus large de l'environnement. Exploitant davantage d'informations temps réel, les nouvelles interfaces homme-machine doivent permettre au pilote de réagir très rapidement, de façon naturelle et spontanée, face aux menaces, et ce quelles que soient les conditions jour/nuit mauvaise météo.

Pour cela, il est nécessaire d'optimiser l'intégration des systèmes et de développer l'homogénéité entre l'ensemble armements-capteurs et l'ensemble des visualisations sans dégrader la vision directe du monde extérieur lorsqu'elle existe.
Ce besoin a conduit à développer des systèmes de visée et de visualisation de casque utilisables quelle que soit l'orientation de la tête du pilote.
Cependant, il convient d'analyser sur le plan fonctionnel ce que l'on peut attendre d'un dispositif de visualisation sur casque en regard des exigences opérationnelles de réalisation de mission.

2 EXIGENCES OPERATIONNELLES

Une analyse exhaustive des exigences opérationnelles conditionne tous les travaux entrepris sur les visuels de casque. Il est un fait que le pilotage et la navigation sont considérablement facilités lorsque le pilote possède une parfaite appréhension du monde extérieur pour son orientation spatiale (horizon défini, relief visible) et son évolution au sein de celui-ci (détection des obstacles artificiels, perception de l'altitude et de la vitesse relative). De plus, la réalisation de missions opérationnelles nécessite l'acquisition visuelle précoce de points particuliers tels que les obstacles artificiels ou repères naturels pour le recalage de système de navigation et le traitement des objectifs. Aussi, lors de l'exécution des missions en très basse altitude l'image, présentée au pilote par le visuel de casque devra recréer le plus fidèlement possible les conditions d'un pilotage et de navigation à vue, avec un enrichissement symbolique pour l'orientation spatiale et la sécurité. L'information présentée ne devra laisser aucun doute quant à sa validité, rien n'étant plus discréditant qu'une mauvaise superposition de l'image recréée et du paysage, lorsqu'il est visible.

L'emploi de tels systèmes par l'aviation de défense aérienne impose que les missions d'attaque air/sol s'exécutent à nouveau en patrouille. Tous les aspects de tenue de place, d'auto-protection et de sécurité au sein de patrouilles lourdes se retrouvent posés.

Enfin, dans un tel contexte, excessivement proche du contexte jour en bonnes conditions météorologiques, l'équipement de tête, jusqu'alors négligé redevient une priorité en terme de masse et de centrage, le facteur de charge augmentant avec les risques rencontrés.

2.1 EXIGENCES DE PILOTAGE ET NAVIGATION

2.1.1 Roulage

Cette phase parfois complexe de jour selon le terrain de départ peut se révéler délicate de nuit sur un terrain sommairement éclairé. Les obstacles au sol doivent être localisés et identifiés à plus de 200 m à ± 90° en avant de l'appareil.

2.1.2 Décollage

La trajectoire de montée doit pouvoir être ajustée pour profiter des obstacles du relief dont les grandes lignes doivent être perçues de 3 à 4 km donnant un préavis de 15 à 20 secondes.

2.1.3 Très basse altitude

Le besoin essentiel est de fournir au pilote une perception du monde extérieur aussi proche que possible de celle qu'il a de jour. Deux aspects sont à considérer. La perception du paysage qui va être survolé à court terme doit être aussi détaillée et lointaine que possible afin d'optimiser le suivi du terrain et l'évitement des obstacles. La perception du paysage latéral doit être assurée pour améliorer la perception de l'environnement global, faciliter l'orientation et tenir une place dans une formation.

Le vol à proximité du sol nécessite une attention soutenue pour des raisons de sauvegarde. Le contrôle des paramètres machine devient particulièrement délicat et doit être exécuté sans recherche en cabine.

2.1.4 Approche

Le retour de mission est un point délicat à réaliser, car si la partie opérationnelle est exécutée, il n'en reste pas moins que tous les avions en retour doivent se présenter selon des procédures définies, à des points géographiques à identifier, en assurant une anticollision à vue lorsque les moyens radioélectriques ne sont pas activés.

2.1.5 Atterrissage

Les espacements étant assurés dans la phase précédente, les conditions de visibilité requises sont du même type que les conditions rencontrées en temps de paix soient classiquement 1000 mètres de visibilité.

2.2 EXIGENCES DE VISUALISATION DE MISSION

2.2.1 Localisation de points remarquables

Au cours de sa navigation, le pilote doit être capable d'effectuer des recalages de son système de navigation inertielle sur des points remarquables par visée unitaire associée à une mesure de distance. De la même façon, en cours de pénétration, le pilote est à même de détecter des objectifs d'opportunité qu'il doit désigner au système pour en enregistrer les coordonnées.

2.2.2 Attaque d'objectifs sol

Deux scénarios d'attaques air/sol (A/S) sont à distinguer :

- l'appui aérien qui correspond aux attaques A/S sur le champ de bataille dans un environnement évoluant rapidement,
- les missions d'interdiction qui se déroulent en arrière de la ligne de front sur des objectifs fixes ou peu mobiles dont la position géographique est connue avant le début de mission.

2.2.2.1 Appui-aérien

Dans ce cas, la phase d'attaque nécessite de détecter l'objectif dans le paysage, de le désigner au SNA si les coordonnées initiales sont erronées, d'utiliser les armements avec leurs performances maximales, et de surveiller le contexte environnant afin d'assurer l'autoprotection et l'anticollision. L'exécution de cette mission en toutes conditions nécessite l'existence de systèmes assurant les fonctions de détection et d'identification à des distances suffisantes pour assurer la sécurité du chasseur. La perception du paysage environnant doit être complète pour donner le préavis nécessaire aux réactions face aux menaces.

L'utilisation des armements classiques dans ce type de mission nécessite de présenter en permanence au pilote et en secteur frontal les informations relatives à la conduite de tir, et de lui fournir une représentation stabilisée du monde extérieur.

2.2.2.2 Interdiction

Dans les missions d'interdiction, les coordonnées de l'objectif sont connues, la phase d'acquisition est assurée par le système d'armes qui indique au pilote la position de celui-ci.

L'utilisation de tous types d'armement nécessite avant tout un excellent recalage, l'objectif n'étant pas survolé lors de l'emploi d armements modernes.

Enfin l'autoprotection au sein de la patrouille nécessite la perception du monde environnant, afin de donner un préavis suffisant pour engager une manoeuvre de défense.

2.3 QUANTIFICATION DES BESOINS

Hormis les besoins chiffrés lors des phases de roulage et d'atterrissage, les chiffres communément affichés lors des phases de navigation et d'attaques sont des conséquences de la vitesse de pénétration. Une visibilité représentant 15 à 20 secondes de vol donne un minimum en deçà duquel la mission ne peut être effectuée à vue.
Les besoins spécifiques à la mission opérationnelle dépendent du préavis nécessaire à une réaction coordonnée et plannifiable :

- la détection d'obstacles de type pylones de lignes "haute-tension" et d'antennes (50 x 3 m) de 4 à 5 km,

- la détection et la reconnaissance de menace Sol/Air ou Air/Air (3 x 3 m) à une distance suffisante pour minimiser les risques soit de l'ordre de 4 à 5 km,

- la détection et la reconnaissance des points de recalage (5 x 5 m) à une distance compatible de l'intervisibilité Air/Sol et des possibilités de mesure de distance typiquement 3 km avec recalage entre 500 et 1000 m en secteur avant,

- la détection et la reconnaissance des cibles à traiter (dim. typ. 10 x 10 m) à une distance compatible de l'engagement d'une conduite de tir soit $\approx$ 10 km

- la précision à obtenir pour le pointage d'un capteur doit permettre d'atteindre une cible de 5 m à 1000 m.

- le débattement angulaire de la ligne de visée doit être compatible de l'autoprotection donc atteindre les valeurs de $\pm$ 150° en gisement et + 90°/- 60° en site.

2.4 EXIGENCES ERGONOMIQUES (Ref.1)

Donner aux pilotes la possibilité d'effectuer de nuit des missions jusqu'ici réalisées de jour, implique la présence d'une défense aérienne plus dense. La présence d'un visuel de casque ne doit, dans ce cadre, en aucun cas entraîner de gêne ergonomique.

Sans reprendre en détail toutes les conditions à imposer, l'équipement de tête ne devrait pas excéder la masse des équipements de tête actuellement en service dans les forces aériennes. Il sera parfaitement équilibré pour permettre au pilote de subir les accélérations d'évolutions ($-1 < G < 5$) en basse altitude et les accélérations d'éjection.
Le champ visuel accessible doit être au plus proche du champ visuel normal, les masques visuels doivent être limités au maximum. La présence d'éléments optiques devant l'oeil est psychologiquement mal acceptée par les pilotes pour des raisons de sécurité en cas d'exposition accidentelle au vent relatif.
Tout en étant confortable, l'équipement de tête doit assurer toutes les fonctions de protection physiologique normale (oxygène, surpression obligatoire) ainsi qu'une protection au risque NBC, avec le minimum de gêne.

2.5 EXIGENCES D'INTEGRATION

Ces exigences couvrent l'aspect emploi d'un visuel de casque dans une cabine évoluée en terme de compatibilité avec les capteurs et visualisations existants. Tous les capteurs doivent être associés pour fournir une information opérationnelle complète, enrichie par le système d'armes.
La vision directe du pilote ne doit pas être altérée par la présentation d'images issues d'intensificateurs de lumière ou de senseur infrarouge, que ce soit du paysage extérieur (majorité du temps) ou de la planche de bord pour la recherche d'informations particulières.
La superposition avec les informations présentées dans les Collimateurs tête haute doit être particulièrement étudiée.

3 SOURCES D'IMAGERIE DISPONIBLES

Des exigences opérationnelles, nous pouvons à l'évidence énoncer, les besoins en images pour présenter au pilote un paysage aussi proche que possible de la réalité. Plusieurs techniques sont disponibles pour donner une représentation du monde extérieur par toutes conditions.

L'intensification de lumière et l'imagerie infra-rouge représentent les deux techniques les plus courantes.

Elles peuvent être complétées par les techniques d'imagerie radar millimétrique et de numérisation de terrain. Ces deux dernières sources d'images ne seront pas abordées dans cet article, mais il faut néanmoins admettre qu'une représentation fidèle du monde extérieur passera par l'utilisation et la synthèse de toutes les images issues de capteurs complémentaires.

Enfin, l'enrichissement de l'information est réalisé par l'emploi d'une symbologie appropriée.

3.1 INTENSIFICATION DE LUMIERE : IL

Le principe utilisé consiste à recueillir puis amplifier la très faible lumière résiduelle toujours présente, même la nuit, et à présenter à l'oeil de l'observateur une image interprétable. Le fonctionnement des équipements IL repose sur la propriété des matériaux constitutifs du détecteur (photocathode) de convertir en électrons les photons provenant de la scène et collectées par l'objectif d'entrée ; ceux-ci sont accélérés et multipliés dans un tube à vide par un champ électrique puis excitent un écran luminescent pour donner une image visuelle (ref. 2).

Trois générations de tubes intensificateurs de lumière reposant sur des composants différents ont successivement été développées. La plus récente, dite de 3ème génération, utilise un matériau pour la photocathode qui permet d'améliorer le rendement de conversions photons/électrons d'un facteur 3. Le déplacement du spectre de sensibilité permet également de bénéficier des caractéristiques spectrales du rayonnement nocturne qui est plus important dans le proche infra-rouge et du comportement des scènes (en particulier la végétation) dont le coefficient de réflexion croît avec la longueur d'onde.

Les performances des tubes IL permettent d'obtenir une image exploitable pour des conditions d'éclairement supérieures à 1 mlx, ce qui statistiquement représente environ 50% des conditions de nuit.

Les dispositifs de vision nocturne à IL présentent un faible encombrement, une simplicité d'utilisation, la possibilité d'être installés sur le casque et enfin ils produisent une image naturelle proche de la vision humaine.

Ils présentent cependant quelques limitations dûes à leur sensibilité aux conditions de luminosité et de visibilité, les portées et résolutions restant limitées.

L'intensification de lumière est utilisée soit directement (Jumelles de Vision Nocturne, ou J.V.N), soit sous forme d'un signal vidéo lorsque le tube IL est associé à un dispositif CCD (ILCCD). Dans les applications visuels de casque, la solution habituellement retenue est le couplage optique entre l'intensificateur de lumière et l'oeil, essentiellement pour des raisons de sécurité, l'image parvenant directement au pilote sans nécessiter de traitement électronique. Cependant, les développements en cours dans le domaine des ILCCD laissent présager l'utilisation de tels dispositifs dans un futur proche (ref. 3).
Les ILCCD ont pour avantage la simplification du schéma optique, une réduction de la masse de l'équipement et la possibilité d'effectuer des traitements d'image, en particulier la fusion avec d'autres sources.

3.2 IMAGERIE INFRAROUGE (IR)

Le principe utilisé consiste à capter et amplifier le flux émis par tout corps dont la température est différente du zéro absolu, et de restituer une image de type vidéo. Compte-tenu des caractéristiques spectrales de l'atmosphère et de la température des scènes à observer, les bandes spectrales utilisées sont l'infrarouge moyen (3 à 5 μm) ou lointain (8 à 12 μm). Les capteurs infrarouges actuellement disponibles sont constitués d'une mosaïque d'éléments sensibles, éventuellement associées à un dispositif de balayage optomécanique et nécessitent un refroidissement à 77°K. Il en résulte que les capteurs IR sont des dipositifs encombrants et coûteux.

Ces équipements d'imagerie infrarouge ont de très bonnes performances de sensibilité et de résolution permettant d'obtenir des portées élevées. De plus, le rayonnement IR est peu sensible aux brumes, fumées et poussières en suspension dans l'atmosphère, ce qui rend possible l'utilisation de ces systèmes non seulement de nuit mais également de jour par visibilité réduite.
Ces équipements peuvent se monter sur une plateforme et ainsi être asservis aux mouvements de la tête du pilote.

Les principales limitations sont leur encombrement et leur coût qui réduisent le champ d'application. Les capteurs IR sont par ailleurs sensibles à la quantité d'humidité présente dans l'atmosphère.

3.3 COMPLEMENTARITE IR/IL

Les conditions difficiles pour les dispositifs à IL sont les nuits sans lune (obscurité profonde) ou les visibilités réduites. De part ces conditions, la disponibilité opérationnelle d'un tel système est limitée à 50%.
Dans le cas des capteurs IR, les conditions difficiles sont les atmosphères chaudes et humides, ou les scènes présentant un faible contraste thermique (scènes "lavées" par la pluie par exemple). La disponibilité opérationnelle de ces équipements, en climat Centre-Europe, peut être estimée à 60%.

Compte tenu de la non-corrélation entre les causes de mise en défaut de ces deux types d'équipement et de la relative indépendance des facteurs de comportement, il est généralement admis que le taux de disponibilité à pleines performances d'un système associant ces deux techniques est de plus de 80% (ref. 4).

3.4 GESTION DES SOURCES D'IMAGERIE

Pour présenter au pilote une image du paysage environnant en vraie direction, les deux sources d'imagerie envisagées doivent être asservies aux mouvements de la tête du pilote.

La fonction intensification de lumière met en oeuvre des éléments de volume et de masse réduits pouvant être intégrés dans l'équipement de tête. Ce principe permet de réaliser simplement l'asservissement en direction et permet d'autre part, en intégrant deux tubes IL, de présenter une image spécifique sur chaque oeil, restituant la perception binoculaire naturelle.

L'imagerie infrarouge met en oeuvre un capteur volumineux qui ne peut être intégré qu'au niveau de l'avion, soit en interne dans la cellule, soit en emport. La présentation en vraie direction dans un visuel de casque d'une imagerie IR nécessite donc de disposer sur le porteur d'un système à ligne de visée mobile couplée à un dispositif de détection de position et d'orientation restituant en temps réel la direction visée par le pilote. Un capteur IL CCD monté sur une plateforme nécessiterait également l'emploi du même dispositif.

Enfin, la compensation en roulis des images peut être réalisée mais reste un sujet controversé. L'intérêt de la compensation des images en fonction du roulis de la tête du pilote est de permettre une superposition image/paysage. Il faut toutefois noter que les conditions d'ambiance lumineuse nécessitant une bonne superposition sont rares.
En l'absence de conclusions formelles sur ce sujet, il semble nécessaire de valider l'intérêt de cette compensation au cours d'une évaluation en vol.

4 REPONSE TECHNIQUE

Le but de ce chapitre est de décrire la façon dont le concepteur du viseur de casque traduit le besoin opérationnel, exprimé par l'utilisateur, en spécifications techniques. On s'est attaché à mettre en évidence les paramètres les plus importants et à montrer comment ils influent sur l'ensemble du projet.

4.1 FONCTIONS NECESSAIRES

Les fonctions nécessaires pour remplir les besoins opérationnels décrits précédemment sont :

- visualisation d'une image du paysage extérieur en vraie direction provenant d'une source d'image appropriée (IR ou IL)
- visualisation d'une image symbolique présentant les principaux paramètres du SNA
- mesure de la ligne de visée du pilote
- protection physiologique du pilote.

La fonction de visualisation permet de présenter au pilote une image conforme au paysage observé.

La visualisation d'une image synthétique satisfait le besoin de présentation au pilote des informations nécessaires à la conduite de sa machine, à la mise en oeuvre d'une conduite de tir et à la compréhension de la situation tactique.

La fonction de mesure de la ligne de visée du pilote permet d'une part, de désigner un objectif au SNA et d'autre part d'asservir une plateforme d'imagerie située en emport.
La protection physiologique du pilote lui permet d'assurer sa mission en toute sécurité.

4.2 CONTRAINTES GENERALES

Les exigences opérationnelles permettent de définir des paramètres incontournables :

- les besoins en portées se traduisent en terme de résolution par des valeurs d'environ 1 mrd pour la détection et 0,3 mrd pour la reconnaissance.
- le champ visuel offert doit couvrir deux besoins : d'une part une résolution maximale dans un domaine angulaire supérieur au champ de vision fovéale de l'oeil soit environ 5°, d'autre part, une résolution moindre dans un champ le plus proche possible du champ visuel naturel afin de percevoir les grandes lignes du paysage et les mouvements latéraux.

Cette multirésolution n'est pas encore accessible, aussi, la valeur communément admise du champ à présenter est comprise entre 30° et 40°. Cette plage représente le meilleur compromis entre le critère "facteur humain", la résolution nécessaire et la masse admissible de l'équipement de tête.

La meilleure information est obtenue par l'utilisation de la binocularité (ref. 5).
Cette solution présente un certain nombre d'avantages. Elle minimise les risques de rivalité oculaire susceptibles d'intervenir lorsque les deux yeux voient des images sensiblement différentes, en particulier en cas de présentation d'une image complète devant un oeil et de l'obscurité devant l'autre. Les conséquences de cette rivalité peuvent être une perte compléte momentanée ou prolongée de l'image, pouvant conduire à une désorientation de l'utilisateur. La présentation de l'image nocturne simultanément devant les deux yeux est donc un gage de sécurité impératif pour un pilote d'avion d'arme.
Cependant, celle-ci est soumise à l'emploi de deux capteurs identiques et indépendants. Si elle est de fait par l'emploi de 2 IL, elle n'est pas envisageable en terme d'encombrement et de coût pour les senseurs infrarouges. Dans ce cas, la biocularité sera préférée.

Les performances de la vision bio/binoculaire sont supérieures à celles de la vision monoculaire, en termes de sensibilité au contraste (gain 40 %), de perception de la luminosité et de perception du bruit lorsque les deux capteurs présentent des bruits spatialement décorrélés.

4.3 PRINCIPE DE PRESENTATION D'IMAGES

L'image du paysage extérieur est présente sur les deux yeux simultanément en binoculaire pour la source IL, en bioculaire pour la source IR.

La présentation en bio/binoculaire d'une scène présente des contraintes de positionnements absolu et relatif des images devant les yeux.

4.3.1 Tolérances

Il est essentiel que le champ de l'image présentée soit situé autour de la position centrale du champ visuel naturel. Les tolérances de positionnement relatif des deux images doivent être respectées afin de ne pas créer des problèmes de fusion d'images ou plus simplement de gêne après un temps plus ou moins long de port de l'équipement. Une étude approfondie effectuée par le "Armstrong Aerospace Medical Research Laboratory" (ref. 6) a permis de quantifier ces tolérances. Les conclusions sont résumées ci-dessous.

- désalignement horizontal
  - < 2,5 mrd en convergence
  - < 1 mrd en divergence
- désalignement vertical
  - < 1 mrd
- différence de grandissement
  - < 3 mrd sur l'axe vertical
- différence en rotation
  - < 1 mrd sur l'axe vertical
- différence de luminance
  - < 25%

Ces données s'appliquent essentiellement à la symbologie. Les valeurs à prendre en compte pour la présentation d'images sont moins contraignantes.

Si la dernière donnée est relativement facile à respecter aussi bien avec une image vidéo projetée à partir des deux tubes à rayons cathodiques qu'avec des IL, il n'en va pas de même des contraintes d'alignement. En effet, ces contraintes doivent être respectées dans toute la plage de réglage interpupillaire des optiques. Elles impliquent la mise en oeuvre de mécanismes robustes, sans jeu mécanique avec un déplacement identique vers la gauche ou la droite. Bien entendu, les caractéristiques doivent être atteintes en restant dans une enveloppe de masse minimale, alors que les contraintes impliquent plus qu'un doublement de masse entre une version monoculaire et une version binoculaire.

4.3.2 Champ

La valeur du champ réel influe sur de nombreux aspects ergonomiques, et en premier lieu sur la masse. En première approche, on peut dire que, toutes choses étant égales par ailleurs, 10° de champ visuel correspondent à un supplément de masse de 200g. La réalisation des fonctions opérationnelles peut être accomplie avec un champ de vision limité à 30°. Une valeur de champ supérieure permettrait d'améliorer le confort visuel du pilote en élargissant sa vision périphérique. Cette augmentation de champ ne pourrait être envisagée qu'à condition que les performances de résolution des capteurs d'imagerie augmentent dans le même rapport.
Cependant, l'adjonction d'une visualisation située en périphérie du champ visuel apportera un complément d'informations pour l'orientation spatiale.

4.3.3 Pupille de sortie

La pupille de sortie est définie comme étant la zone de déplacement de l'oeil par rapport au dispositif optique dans laquelle la vision de l'intégralité de l'image est conservée. Cette notion est aussi importante que celle de champ.
Pour la valeur de champ spécifiée, la dimension de pupille minimale à retenir est 10 mm de façon à couvrir le débattement de l'oeil correspondant à une vision en bord du champ de l'image.
En considérant les mouvements résiduels du casque sur la tête, le diamètre de la pupille de sortie du dispositif optique doit donc au moins être égal à 15 mm.
Le diamètre de pupille doit être respecté non seulement au centre du champ mais encore en bord de champ. Tout comme le champ, une augmentation de la pupille a un impact direct sur la masse (ref. 7).

4.3.4 Tirage d'anneau

Le tirage d'anneau est défini comme étant la distance minimale entre l'oeil et l'élément optique le plus proche. Une valeur minimale de 25 à 30 mm est suffisante pour assurer la compatibilité avec le port de lunettes de correction ou avec un équipement de protection NBC.

4.3.5 Transmission de la voie directe

Une transmission importante de la voie directe a un impact immédiat sur la luminance de sortie des sources d'images. Une valeur de 30% est suffisante pour le pilotage de nuit.

4.4 IMAGERIE

4.4.1 Format

Le besoin à satisfaire est d'assurer la compatibilité du viseur de casque vis à vis du standard vidéo des capteurs d'imagerie disponibles.
Le viseur de casque devra donc être compatible de la présentation d'une image vidéo conforme au STANAG 3350 B (625 lignes, 50 Hz, format 4/3).

4.4.2 Luminosité

La luminosité de l'image vidéo présentée doit être compatible de l'exploitation par le pilote qu'elles que soient les conditions d'ambiance lumineuse.
Elle doit d'autre part être réglable doit être réglable continuement. Un asservissement automatique de luminosité est souhaitable.

4.4.3 Contraste

L'image vidéo présentée dans le casque doit disposer d'un contraste suffisant à l'interprétation.
Le contraste de l'image vidéo doit être supérieur à 5,6:1 pour garantir la visualisation d'au moins 6 niveaux de gris.

4.4.4 Résolution

Les besoins de résolution nécessaires pour la détection et la reconnaissance sont :
- détection : résolution > 1 cycle/mrd
- reconnaissance : résolution > 3 cycles/mrd

Les deux capteurs utilisés (IL-IR) couvrent le besoin. La détection est assurée par les IL et les capteurs IR, la reconnaissance par les capteurs IR. Dans ces conditions, les images utiles pour la reconnaissance seront présentées sur une visualisation annexe où la fonction agrandissement sera utilisable.

Pour des raisons de sécurité, seule une image à l'échelle 1 sera présentée en visuel de casque. Les risques de désorientation spatiale sont importants lors de la décorrélation de l'échelle de l'image et de la réalité, même si la sélection de l'image est commandée par un sélecteur instable.

4.4.5 Symbologie

Contraste et résolution caractérisent la symbologie.

Le contraste est défini par le rapport suivant :
$C = (L1 + L2)/L1$

avec L1 la luminosité du fond (image vidéo ou paysage extérieur) et L2 la luminosité des symboles.
Les performances de résolution de l'oeil nécessitent de disposer d'un contraste des symboles par rapport au fond supérieur à 1,3:1.
Concernant la résolution, la largeur de tracé des symboles sera de $1,0 \pm 0,2$ mrd.
Enfin, la position du réticule de visée sera ajustable dans le champ afin de déterminer expérimentalement la position optimale pour une application Air/Sol sur avion d'armes.

4.5 PERFORMANCES DE MESURE DE LA LIGNE DE VISEE

4.5.1 Débattements angulaires

Les besoins opérationnels recensés pour les capacités de débattement angulaire de la tête du pilote sont les suivants :

- Visées Air/Sol :
  - Gisement : ± 90°
  - Site : - 60°, + 30°
  - Roulis : ± 30°

- Autoprotection :
  - Gisement : ± 150°
  - Site : - 60°, + 90°
  - Roulis : ± 45°

4.5.2 Précision

Les besoins en précision statique sur la mesure de la ligne de visée du pilote sont de deux types :
- désignation d'un objectif : 0,25°
- asservissement d'un capteur IR : la précision nécessaire doit être déterminée en fonction du capteur mis en oeuvre et des caractéristiques de la chaine d'asservissement.

La précision à obtenir dans la superposition des images avec le monde réel reste à définir expérimentalement. Les écarts admissibles sont ceux qui n'engagent pas la sécurité et ne discréditent pas l'information lors de la vue simultanée des images capteurs et du monde réel.

De la même façon, la précision dynamique à obtenir dépend des capteurs utilisés pour les fonctions de désignation (radar ou autodirecteur) et du capteur IR asservi. Une précision dynamique de 1,3° à 95% pour un mouvement à 30°/s peut être retenue à priori.

4.6 CASQUE SUPPORT DU VISUEL

La prise en compte simultanée de toutes les exigences opérationnelles de protection physiologique et d'ergonomie a permis de mettre en évidence l'existence d'une solution originale, le casque intégral.

4.6.1 Protection physiologique

La protection aux chocs et la résistance à la perforation sont excessivement bien assurées. Il en va de même pour la protection faciale et oculaire en cas d'exposition au souffle aérodynamique jusqu'à 625 Kts.
La protection respiratoire comprend d'une part l'oxygénation du pilote et d'autre part les fonctions de surpression respiratoire en fonction du facteur de charge ou en cas de dépressurisation cabine.
La protection visuelle est assurée contre le soleil lorsque nécessaire, les reflets ou les rayonnements laser.
L'isolation phonique procurée est identique à celle des casques standards. Cependant, l'utilisation de filtres actifs peut être envisagée.
La formule "Casque intégral" facilite considérablement la protection NBC tout en maintenant toutes les capacités opérationnelles.

4.6.2 Ergonomie

La masse de l'équipement de tête est minimisée de façon à éviter toute fatigue ou gêne pour le pilote. Selon le masque utilisé, la masse est comprise entre 1,8 et 2 kg.
La position du centre de gravité résultant (tête + équipement de tête) est conforme aux tolérances admises à l'heure actuelle.
Le casque possède d'autre part une personnalisation adaptée à chaque pilote. Elle participe à la tenue de l'ensemble tête-casque tout en assurant un excellent confort.
Le principe de visualisation retenu étant de type binoculaire, un réglage du module optique permet d'adapter l'équipement de tête à l'écart interpupillaire du pilote.

5 CONCLUSION

Le Visuel de Casque ainsi défini répond aux exigences opérationnelles. Il donne au pilote les moyens de contrôler son appareil et réaliser sa mission par tout temps dans de bonnes conditions de sécurité.
Cependant, et pour ces mêmes raisons, la reconnaissance des objectifs nécessitant des changements d'échelle des images ne pourra être assurée que dans une visualisation moyenne ou latérale.
Cette solution représente le compromis idéal aujourd'hui en regard de l'état de l'art en la matière.

Les évolutions futures du visuel de casque devront prendre en compte les caractéristiques physiologiques du capteur rétinien pour asservir la résolution de l'image présentée à la position de l'oeil. Cette solution permettra de toujours présenter au pilote l'image de plus haute résolution sans pour autant nécessiter des capacités et des vitesses de calcul accrues.
Les différents capteurs ou bases de données embarqués devront participer à la création de l'image pour fournir au pilote un seul type d'images fusionnées plus ou moins enrichies en fonction des capacités instantanées de chaque senseur.

Mais à ce stade se posera la question de la superposition précise des images issues des capteurs et du monde réel. Une mesure beaucoup plus précise de la ligne de visée peut, en valeur absolue, apporter la solution. Cependant les fréquences de calcul de cette ligne de visée ne vont elles pas créer un obstacle déterminant ?
Dans quelle mesure cette superposition parfaite est-elle nécessaire, surtout si les conditions ne permettent pas la vue de paysage ?
Dès lors que le champ utilisé par les différents dispositifs optiques permettra de fournir au pilote les alertes en champ visuel périphérique, et que les capteurs couvriront le même espace que l'oeil du pilote avec une précision de la ligne de visée ne mettant pas en jeu la sécurité, alors il sera possible d'envisager l'utilisation du cockpit fermé.

Cependant, dans ce contexte, le pilote devra tout de même, être capable de se construire au mieux sa propre représentation mentale de la situation sans laisser au système, le soin de décider pour lui.
Quelles images doit-on présenter au pilote ? Quelle redondance de moyens faut-il lui fournir pour lui assurer le jugement d'une situation donnée et les décisions en découlant ?

Ces grandes questions posées n'empêchent cependant pas de penser que le cockpit fermé ou virtuel n'est plus aujourd'hui inaccessible.

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THE MOD(UK) INTEGRATED HELMET

TECHNICAL DEMONSTRATOR PROGRAMME

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1. SUMMARY
As a result of progressively adding on capabilities to the basic protective flying helmet, present solutions to operational requirements result in barely acceptable flying helmet assemblies. The devices which provide these capabilities must all be compatible with each other, with the rest of the pilot's Aircrew Equipment Assembly (AEA) and with the aircraft. Often conflicting requirements result in compromises being made. Fundamental rules of optics cannot be changed, and in general, improved optical performance results in larger, heavier head-borne load.

Heretofore, the solutions have been engineered by several companies, each specialising in a particular discipline, resulting in the present 'add-on' philosophy. The UK MOD has taken the view that the time is appropriate for Industry to adopt a more coordinated approach. The Integrated Helmet Technical Demonstrator Programme (IHTDP) is aimed at encouraging a helmet to be designed from the outset with wide ranging capabilities, stimulating Industry to form consortia to produce a truly Integrated Helmet. The paper discusses the background to the programme, the requirements from the operators' point of view and describes the specification of requirements.

2. THE DEVELOPMENT OF THE FLYING HELMET
The modern flying helmet has evolved over a period of almost 50 years. Initially it was no more than a 'hard hat' affording protection to the pilot should he have to eject from his aircraft and at the same time offering a place upon which an oxygen mask and communication facilities could be conveniently attached. The modern helmet, typified by the RAF Mk 10 ALPHA helmet (Fig.1), makes use of modern materials to produce a light-weight, comfortable, effective element of his AEA.

In recent years, the operational advantages of using the helmet as a platform for enhanced vision and weapon aiming devices has placed upon helmet designers the difficult task of meeting the operational requirements and producing a helmet assembly which meets the aeromedical and human engineering aspects of flying in a physically demanding cockpit. As fast-jets become more agile, the g loads and g on-set rates become extreme. Operating for lengthy periods under loads approaching 9 g calls for pilots with a high degree of physical robustness. Any mass on the pilot's head must entirely justify its existence.
However, it is generally accepted that helmet-mounted devices offer a significant operational advantage and could be the deciding factor in determining whether the pilot reaches his objective, wins the engagement, survives or is shot down.

Helmet-mounted devices have, in general, offered a particular capability. The next few sections deal very briefly with these capabilities.

2.1 Helmet mounted sights
The simplest device is a helmet-mounted sight which provides a fixed aiming mark to the pilot as a monochromatic, small field of view, collimated reticle. In general the virtual image is formed on a reflecting patch on the clear visor (Fig.2). By measuring the pilot's direction of gaze with a head position sensing system and slewing a weapon sensor, such as an infra-red (IR) seeker-head, it is possible to lock the missile to a target off the aircraft boresight. In this manner his firing opportunities are increased with obvious operational advantages.

2.2 Helmet-mounted Displays
If the fixed reticle is replaced by a

display source capable of providing cursive symbology, such as a crt, more complex information similar to that of a Head Up Display (HUD) may be provided. However, this imposes more demanding optical requirements as the increased field of view required to present the flight data leads to larger optical elements (Fig 3). Inevitably this increases the mass and a compromise between field of view, exit pupil, eye relief and mass must be made to meet the requirements optimally.

Taking this concept further to a raster based crt system, an image from an electro-optical (EO) sensor such as a low light TV or IR camera may be presented to the pilot with superimposed flexible display symbols giving flight and mission related data (Fig 4). If the EO sensor is mounted on a gimballed platform which is driven by a head position sensing system, the visually coupled system thus formed allows the pilot to view the EO scene throughout a field of regard limited by the platform gimbal limits or his own ability as a contortionist. Experience has shown that this type of image must be viewed binocularly to prevent pilot stress, fatigue and even nausea due to binocular disparity.

2.3 Night Vision Goggles
Perhaps the most familiar helmet-mounted device is the night vision goggle (NVG). Configured binocularly and attached to the pilot's helmet, NVGs provide an intensified image of the view. Adding approximately 800 gms to the helmet, they were initially used in helicopters where the lower g loads were acceptable, considering the significant advantage of being able to operate in the dark.

However, these NVGs were soon applied to fast-jets, as illustrated in Fig.5 which could thus operate throughout the 24 hr period and reap the operational benefits that this offered. In this environment, not only did the additional weight (acting forward of the head c of g) present a problem during normal flight, where higher g loadings are the norm, the results of ejecting whilst wearing the NVGs would be catastrophic. The UK MOD were committed to this type of device for the SR(A)1011 programme and attempts at reducing the mass and forward c of g have been made with some success. An automatic separation device to remove them during the ejection sequence had to be developed. Although this at least prevents breaking the pilot's neck, the hazard of 800 gms of hardware loose somewhere in the cockpit during the ejection sequence is still a cause for concern.

The above paragraphs summarise the separate capabilities which have enhanced the attributes of standard flying helmets. A more thorough treatment of these and other helmet-mounted devices can be found in Ref 1.

3. THE REQUIREMENT FOR AN INTEGRATED APPROACH
Examples of all the above devices exist and the many variants providing a particular capability bear witness to the ingenuity of designers. However, they invariably share the common factor of being an addition to a helmet. Each device provides its own singular and unique capability. It is apparent that current and imminent requirements demand combinations of the separate capabilities described above. For example, the combination of image intensification for night use coupled with a comprehensive day helmet-mounted display. This combination not only presents the designer with difficult and competing design requirements, it forces the weight of the device to a level which is incompatible with the operating environment.

With this as a background, the UK MOD instigated a Technical Demonstrator Programme for industry to produce an Advanced Integrated Avionic Helmet (AIAH) designed from the outset with all these capabilities. It is important at this point to look in some detail at the full reasoning behind launching this programme.

3.1 The Team Approach
There was a strong belief that to meet the weight and performance requirements for fast-jet operations, an integrated approach was a prerequisite. Helmet development has historically been conducted by several interrelated but separate technical disciplines. For example, the design of the helmet shell has been conducted with parameters such as mass, strength, comfort, and penetration resistance uppermost in the designer's mind.

The requirements for life support functions such as provision of oxygen, protection against blast, NBC and visual threats were all considered as extras. The requirements for visual enhancements have had no significant effect on the design of the helmet shell. Similarly, the optical design of helmet display devices has generally been based on existing helmet shells. The display systems manufacturers have not been able to influence helmet design, only to make best use of the available helmet shells.

Although aeromedical experts have offered their advice on life support and pilot protection aspects, their

involvement in HMD programmes would appear have been retrospective design advice rather than at the critical design concept stage.

It is believed that one of the keys to successful helmet system design is the formation of a design team consisting of all helmet related expertises, aeromedical, optical, display, materials, etc. and it was hoped that the TDP would encourage this.

3.2 Human Factors

It was realised that there was a lack of experience in operating with these devices and their eventual success depended upon understanding the human factors issues involved. These factors can be separated in terms of the pilot's psychophysical issues and human engineering issues.

3.2.1 Psychophysical Issues

The use of displays which provide a virtual image present many effects to the viewer. The Head Up Display, which evolved from the gyro gunsight, has overtaken panel mounted instruments as the primary display surface in military fast-jets, and was the first cockpit display device to produce a virtual image. It is known that, although the display is collimated, the pilot cannot concurrently merge his attention to the symbols and the view through the combiner but effectively switches his attention between these two sources of information. With the addition of a sensor image, such as FLIR, on the HUD there are three images, nominally at infinity, between which the pilot has to split his attention. There is evidence that pilots have experienced some problems in flying with information supplied in what amounts to three image planes, ie the symbol plane, the EO image plane and the real world plane.

In a binocular system, each eye is provided with its own optical system and, strictly speaking, its own (different) image. Biocular systems provide each eye with the same image. The amount of overlap of the fields of view of each eye can be varied to extend the instantaneous field of view of the device, the overlapping area having the potential to provide stereoscopic imagery. However, since the overlap area is provided twice, this can appear as a brighter image to the viewer and the area immediately adjacent to and outside the overlapped region can give the appearance of a much less bright image. This phenomenon is looning, and image processing to minimise the effect needs to be carefully accomplished to prevent the highly distractive effect negating the field of view advantage gained by not fully overlapping the fields of view.

The perception of distance is based upon several factors, such as the size of an object, relative brightness, focal distance of the eyes and their convergence. In synthesising a stereo image it is crucial that these factors are taken into account. Any inaccuracies could provide false stereo cuing. For the eyes to fuse the two images of a binocular display to form a complete image, the eye/brain combination must be given enough information to interpret correctly the visual data being provided. Apparent or real conflicts between any of the factors which contribute to a stereoscopic image can give rise to mental and optical discomfort initially, and ultimately to higher workload, and possibly nausea and disorientation.

The provision of binocular symbols must be carefully considered. Although the optics can be set up to provide comfortable viewing at infinity, when attention is given to objects placed nearer than infinity the natural convergence of the eyes will cause the symbols to appear doubled. The pilot will either be able to fuse the outside scene or the symbols but not both.

The above factors need to be addressed thoroughly to provide a comprehensive data-base from which future equipment specifications may be determined.

3.2.2 Human Engineering Issues

In this section the physical issues relating to the operational use of helmet-mounted displays is discussed.

Comfort over enduring periods is a high priority for aircrew acceptance of the device in service.

The importance of the additional head-borne mass has already been discussed. Even supposing the mass is acceptable, the device must integrate with the pilot's aircrew equipment assembly (AEA), must allow the pilot to operate his aircraft in an unhindered fashion. The umbilical which connects the helmet to the aircraft system must be carefully integrated with the AEA, seat and aircraft to allow normal and emergency egress from the cockpit and not compromise a safe ejection. The design must be compatible with the use of NBC equipment, have sufficient eye relief to be safe and compatible with the use of aircrew spectacles. Sizing of the helmet and adjustments must allow for the full anthropometric range of aircrew. The experience provided by the Integrated Helmet TDP will assist in determining these factors.

3.3 Display Symbology

Considerable experience has been gained in the UK with a variety of helmet-mounted display devices of limited capability. A significant amount of this work was based on simulator studies and helicopter flight trials at DRA Farnborough using a relatively narrow field of view binocular HMD in a visually coupled system configuration (Fig 5). The evidence to date suggests that the design of symbol formats is of vital importance . The 'HUD on the head philosophy' is too simplistic an approach when the display is perpetually in the pilot's field of regard. Particular areas of concern are the amount of information presented, the optimum methodology of moding the display for different phases of the flight and the most suitable technique for ensuring the pilot's attitude awareness at all times. At night in particular, the pilot must retain his awareness of the aircraft attitude and his direction of gaze relative to the aircraft axes.

By providing a flexible, comprehensive symbol generation capability this programme will enable an exhaustive airborne study of format design.

3.4 Technology level

A major factor driving the Advanced Integrated Avionic Helmet Programme was that the experience gained through the programme would enable the MOD to have the necessary expertise to write realistic specifications in the future. For this reason, it was important that the hardware be delivered in the shortest possible timescale. It followed that the level of technology called for had to be current state of the art with a low technical risk and an associated high degree of confidence that contract would run to time. There was nothing to be gained from a prolonged development programme with a high element of technical risk. It was understood from the outset that this programme was one element in a multi-pronged attack on the problem. Other programmes would encourage the development of new technologies which could be applied to future advanced helmets.

4. THE OPERATORS' POINT OF VIEW

For many years, ground attack aircraft have had an impressive day only, good weather, capability. This has not been matched by their ability to operate in bad weather or at night. One need look no further than the recent Gulf War to see the effectiveness of operating at night.

In the late 1960s, the introduction of the Head Up Display allowed the pilot to have all essential flight information displayed ahead of him, superimposed on the real world. This allowed him more time with his head "out of the cockpit". The ability to display essential flight and weapon aiming symbology directly in the field of view of the pilot, was a major step forward. The reduction in the cockpit workload significantly enhanced flight safety and improved mission effectiveness. However, as aircraft avionic and weapon systems have become more complex, it has become more difficult for the pilot to assimilate all the essential information from the cockpit displays. Indeed, he cannot take full advantage of the increased capability offered. The narrow and fixed field of view of the HUD directly ahead of the aircraft, on the other hand, was still a major limitation of the system.

With the arrival of night vision sensors, such as FLIR and NVG, the limitations of the HUD fixed field of view unduly restricted the potential of the system. The development of the wide angle raster scan HUD, improved this position in that FLIR images could be reproduced head-up. Moreover, the improved FOV significantly enhanced crew performance. Despite these improvements, the pilot was still not provided with all-aspect night vision sensors. A way forward which partially solved the all-aspect issue, was to mount NVGs on the pilot's flying helmet. Whilst helmet mounted NVGs have proved most successful operationally, there are serious disadvantages of "bolting on" a considerable extra mass to the front of the helmet. The pilot uses the NVG to fly at low level and to manoeuvre when the light levels permit. The ability to look around coupled with the natural appearance of the image, offered an acceptable capability despite the poor resolution of NVGs relative to the FLIR. The advantage of FLIR/HUD combination, with its high definition image ahead of the aircraft, is that it is not dependent on ambient light levels. Moreover, the ability to indicate potential target hot spots on FLIR systems, has considerable operational advantages.

4.1 The Requirement

The future is clear, we should seek to combine all the visual and physiological advantages of FLIR and NVG within a fully integrated system. The primary function of the helmet is to protect the crew from injury. It should be robust, light and comfortable to wear for long periods of time and be capable of displaying flight information, weapon sighting and night vision facilities. The visor should

also provide the pilot with protection against laser dazzle or damage. The Technical Demonstrator Programme (TDP) is one element of a two phase approach for a helmet that has all the current safety standards for crew protection. The first phase offers a full system with equipment that is developed from existing technology hardware. The programme calls for a low technical risk yet highly capable state of the art solution. The second phase intends to support enhanced technology for specific parts of the system, where it is known that these enhancements are not possible, or available within the timescales of the first phase.

The balance of flight, weapon and night vision symbology is critical to avoid cluttering the display. The display priorities for different phases of the mission and the need to select different display formats will be studied in depth to help define future standards for production equipments. The overall accuracy and flexibility of current systems is below that required for visually coupled systems and only suitable for aiming smart weapons such LASER Guided Bombs (LGB) or Air to Air Missiles (AAM). Performance improvements, approaching that of a HUD, to provide a display surface well registered with the outside world is fundamental in terms of display brightness, pointing accuracy and linearity. This would permit the use of early generation weapons which require precision aiming from the launch aircraft.

In summary, the primary function of the helmet is to protect the pilot from injury in a high acoustic environment. From the operator's point of view, the following factors should be given highest priority:- The helmet should have minimum on-head mass with good balance, stability and comfort. The man-machine interface (MMI) should be simple and compatible with current AEA. If the helmet was modular in design, but not role specific, the design could reflect different roles and applications. Progress could then be made towards a common helmet for different types of aircraft. Future techniques of sensor fusion coupled with the optimum use of FLIR, NVG and Radar or synthetic scenes, will increase our operational effectiveness. By optimising the MMI, mission effectiveness is enhanced thus further depriving the enemy of a place to hide.

5. CONTRACTUAL CONSIDERATIONS

The specification of requirements was drawn up by AES with assistance from several areas of expertise within the MOD Research Establishments, notably Flight Systems Department DRA Farnborough, and the RAF Institute of Aviation Medicine.

The specification was intentionally demanding to enable MOD to form an opinion of industry's real current capability, and it was fully expected that there would be no fully compliant bids.

Current MOD procurement policy dictated that the contract should awarded on the basis of an open competition. The specification was therefore sent out as part of the Invitation To Tender (ITT) to over 20 firms from the international avionics industry. The specification was accompanied by a document giving Special Instructions to tenderers in which it was made clear to prospective bidders that hardware delivery would be 18 months after receipt of contract. Tenderers were asked to include in their proposals system commissioning and support of the equipment during the flying phases.

The ITT went out December 1990 and four months were allowed for the respondents to formulate their responses. Some of the recipients had questions regarding certain aspects of the specification, mostly points of clarification. In accordance with the normal protocol for competitive tenders these were formally circulated to all bidders together with the official responses.

Four firms responded to the ITT and their proposals were distributed for assessment in May 1991.

Due to the commercially sensitive nature of the subject matter a nominated team of assessors was selected from the relevant areas of MOD. Each member was given precise instructions regarding their terms of reference and their particular areas of concern. The technical assessors were not made aware of the commercial aspects of the bids, nor were they advised of the quoted costs or the overall value of the contract.

The main areas of concern in technically assessing the bids were the tenderers' understanding of the requirements, the technical compliance with the specification, and the confidence which could be placed in the supplier meeting his claimed degree of compliance. As stated earlier, the short timescale for delivery implied almost off-the-shelf hardware. A significant element of the assessment was the perceived technical risk in the supplier meeting the claimed performance. The contract was not intended to be a developmental

exercise, neither was it intended for pursuing technology research.

A preliminary assessment meeting was held to ensure that all parties understood their terms of reference and to confirm the method of assessment. At this stage it was evident that most of the assessors shared a common view regarding the likely order of bids, although this could not be allowed to effect the individual conclusions of the assessment panel members. Written reports giving comments and conclusions were required by mid-July 1991 in preparation for the final technical assessment meeting in late July 1991.

It is not appropriate in this paper to discuss the solutions proposed nor the reasons for choosing the eventual winning bid. However, a rigorous methodology for marking the bids for technical merit was developed, based on the degree of compliance, the level of importance of various aspects of performance, and a confidence rating based on the assessors' judgement of the claimed performance.

Similar assessments were made on the relative commercial merits of the bids based on the commercial proposals, including costs, although this activity was conducted separately from the technical assessment and by different panel members.

The contract was let in January 1992 with delivery 18 months later in July 1993.

6. TECHNICAL SPECIFICATION

This section gives a cardinal point specification for the performance of the Integrated Helmet. The specification as issued to the potential tenderers was much more detailed and included other aspects not covered here. However, it is the intention that the details given below will give the reader some appreciation of the level of performance required.

6.1 Role of the Equipment

The equipment will be for aircrew flying fixed wing aircraft in most operational roles, with battlefield helicopters as a secondary consideration. It will be used by day and night where minimal reference to cockpit displays is essential. The sub-systems comprising the Advanced Integrated Avionic Helmet System are a light-weight helmet, compatible with existing UK AEA forming a stable platform for mounting the avionics and optics, communication sub-system, noise attenuation and aircraft interfaces. Third generation standard image intensification in a binocular format, integrating symbology and imagery from the video sub-system will provide integrated imagery to the eyes. A video sub-system interfacing with a forward looking infra red camera (FLIR) and avionics to provide thermal imagery, flight and weapon aiming symbology to the display sub-system. A helmet pointing sub-system will integrate the helmet-mounted avionics with the aircraft and weapon systems.

6.2 General

The system is to be optimised for fast-jet aircrew, particularly with regard to total head mass and centre of gravity. No aspect of the design shall increase the risk of injury to the aircrew during emergencies including escape, descent and land or sea survival. A fully integrated binocular display of imagery is required. Should a modular system be proposed, it shall be designed for single handed fitting when wearing NBC AEA and suitable for cockpit stowage.

6.3 Helmet and Communications Sub-Systems

The helmet shall provide protection against blast, high ambient light levels, MDC spatter, debris during ejection, birdstrike, etc. Sound attenuation shall be provide, active noise reduction being highly desirable provided no mass penalties are evident. Good helmet stability to retain the eye within the exit pupil throughout typical flight and operational envelope of agile fast-jet aircraft.

6.4 Display Sub-System

6.4.1 General

The optical system shall allow the pilot to view binocularly imagery from the video sub-system and Third Generation Image Intensifier imagery overlaid in space. A direct 'see-through' with the naked eye over the whole defined field of view shall be provided.

6.4.2 Field of View (FOV)

The Image Intensifier images shall be circular 40°- 45°.
The video image shall be displayed at 40° by 30°.
The angular subtense between the axes of left and right fields of view must not exceed 10°.

6.4.3 Unaided eye FOV

At least 160° horizontal x 80° vertical. Individual visual obstructions shall be less than 2° subtended angle with no obstructions within the display fields of view.

6.4.4 Linearity

Any EO image of an object at infinity

shall be within D degrees of its true angular position where D = 0.1 x R where R is the true angular subtense.

6.4.5 Veiling Glare
2% on axis. Haze less than 0.5%

6.4.6 Alignment
Misalignment between any image at the centre of the FOV and the infinity outside world shall be less than 1.0 mrad.

6.4.7 Eye Relief and Exit Pupil
Eye relief: 30 mm min. Exit pupil: 15 mm min.

6.4.8 Virtual Image Distance
The image viewed through the display optics shall be focused between 500 m and true infinity. The system shall provide a means of minimising any adverse optical effects when the aircrew's eyes converge to focus on directly viewed near objects.

6.4.9 Transmission and Reflectance
Minimum photopic transmission of 70% for directly viewed objects. Display optics shall have a minimum transmission of 25% between 540 and 550 nm.

6.4.10 Magnification
System magnification 1.0 ± 0.04 with each monocular assembly matched to within ± 0.02.

6.4.11 Resolution
At least 0.8 cy/mrad on axis for full FOV. At least 0.73 cy/mrad 10° off axis.
At least 0.73 cy/mrad with pupil displaced 5 mm from centre of optical axis.

6.4.12 Brightness Gain
Not less than 2000 cd/m^2 per cd/m^2 with a difference between monoculars of less than 10%.

6.4.13 Image Intensification
The image intensification shall allow the pilot to use normal visual flying techniques in light conditions down to overcast starlight, 5 x 10^{-4} lux and shall have a third generation spectral response. The tube specification proposed shall identify significant improvements over existing specifications in the areas of blemishes, fixed pattern noise, scintillation, gross and shear distortion (if a fibre optic twister is used).

6.5 Video Sub-System
A video sub-system based on a high performance miniature crt or display device of similar performance to provide imagery from a FLIR thermal imager, weapon system data and flight symbology to the display sub-system.

6.5.1 Electrical Interfaces
The system shall provide an interface with the aircraft avionics using a MIL STD 1553B interface. It shall also provide an interface with the Helmet Pointing sub-system.

6.5.2 Video Interface
625 line 50 Hz CCIR standard.
Additional interfaces to allow growth potential for future high definition video standards and planned FLIR improvements are desirable. The system shall interface with the SR(A) 1010 fixed FLIR. As the helmet traverses the FLIR field of regard the system shall slew the displayed FLIR image to maintain registration of the FLIR image with the outside world to within 1 mrad. The image shall be stabilised with reference to airframe to compensate for both deliberate and inadvertent head motion due to vibration/turbulence.

6.5.3 Brightness
Automatic brightness control shall be provided together with a manual override. The symbology shall be legible when viewed against a background luminance of 35000 cd/m^2.

6.5.4 Symbology
The system shall provide simple flight data, weapon status and aiming symbology configured initially in a typical HUD format. The provision of information shall be software controlled allowing flexibility to change content and format. A means of quickly decluttering the display in flight shall be provided.

6.5.5 Pilot Controls
The pilot shall be provided with adequate controls to operate the system in flight.

6.5.6 Linearity
The video system shall provide all adjustments required to ensure that the video images as seen at the eyes are aligned with real objects at true infinity to within 1 mrad.

6.5.7 Resolution (with CCIR TV input)
Over the full exit pupil and with the image rotated through 0°, 45°, and 90° the system shall display a bar pattern of frequency 8 MHz at full contrast against a background luminance of 5000 cd/m^2 (also 4 MHz at 20% contrast).

Similarly, with a background luminance of less than 0.1 cd/m^2 a full contrast bar pattern of 6 MHz shall be displayed (also 3 MHz at 20% contrast).

6.5.8 Contrast
The system shall be capable of maintaining a minimum contrast of 1.2

against a real world luminance of 30,000 cd/m^2.

6.5.9 Symbology
The system shall be capable of displaying symbols of line width 1 mrad approximately to a positional accuracy consistent with the linearity and magnification requirements.

6.5.10 Grey Scale Resolution
The video sub-system shall be capable of displaying eight shades of grey including black, where shades are related by a level factor of 1.4.

6.6 Helmet Pointing Sub-System
Components shall not hinder normal aircrew tasks or mobility. The system shall be capable of functioning with inputs from two helmets. Outputs of position and angle shall be provided in a recognisable and standard coordinate system referenced to aircraft axes.

6.6.1 Minimum Head Motion Box (referenced to aircraft axes):

Translation		Rotation	
x	360 mm	Pitch	±80°
y	300 mm	Roll	±70°
z	200 mm	Yaw	±160°

6.6.2 Linear Resolution
< ± 1 mm

6.6.3 Angular Accuracy

Within the ±30° forward cone	< 1 mrad
Within the ±80° forward cone	< 5 mrad
Elsewhere in head motion box	< 20 mrad

6.6.4 Angular Resolution
< 0.5 mrad

6.6.5 Minimum Update Rate
50 Hz

6.6.6 Boresighting
A means of in flight boresighting the helmet optical sightline with an aircraft datum is required to an accuracy of 0.5 mrad.

6.7 Design and Construction

6.7.1 Mass
Maximum permitted head mounted mass is 2.0 Kg (excluding oxygen mask)
Desirable mass 1.4 Kg (excluding oxygen mask)

6.7.2 Centre of Gravity (CG)

±y direction	As per unadorned head.
±x direction	As far rearwards as possible within the bounds of the natural CG and a point above the rotation point of the head.
±z direction	As close as possible to the natural CG but not exceeding 40 mm above natural CG, and highly desirable that it be as low as possible.

6.7.3 Maximum Dimension Profile
No part of the helmet shall protrude more than 200 mm upwards or 225 mm rearwards, from the eye position. The helmet shall not be wider than 280 mm. Aircrew mobility when wearing full AEA shall not be impeded.

6.7.4 Connectors and Cables
Any connection to the head mounted systems shall be accessible to the aircrew, provide single handed connection and disconnection with protection against inadvertent disconnection and shall separate automatically on ejection. Electrical discharge protection shall be provided. Any cables shall not inhibit aircrew mobility in normal or emergency tasks.

6.7.5 Environmental
The equipment design should be consistent with operating in a fast-jet environment.

Note: Standard environmental tests and performance requirements were given in the specification covering temperature, pressure, humidity, vibration, shock etc.

6.7.6 Availability
The equipment shall be designed for a service life of 5 years.

6.7.7 Reliability
A mean time between defects of 1000 hours shall be achieved. Flight safety critical failures shall not exceed 1 in 10^6 flying hours.

6.7.8 Maintainability
The mean active repair time at first line shall not exceed 30 min and it shall be possible for 90% of all repairs to be completed within 1 hour.

6.7.9 Contractor Support
For a period of 18 months from delivery of the equipment the contractor shall provide engineering support, repair and maintenance including the provision of spares, support any software changes, updates or reprogramming required either due to failures or as part of an agreed programme of software development.

6.7.10 Design Approval
Limited type approval testing shall cover the following aspects:

Crash safety/shock including impact and crash deceleration tests
Vibration

- Temperature/pressure
- Explosive decompression
- EMC
- Compass safe distance
- Performance in sustained acceleration
- Air blast to 450 knots
- Ejection ramp tests
- AEA compatibility
- Emergency egress

7. CONCLUDING STATEMENTS

It will be seen from the above that the specification was quite demanding, the main features making it so being the large binocular FOV, the large exit pupil, the requirement for image intensification and concurrent sensor imagery and, last but not least, the all up mass of 2.0 Kg maximum. In addition to these physical requirements, the optical/display requirements called for a somewhat better performance than current systems' known capabilities.

There were good reasons for demanding this performance, apart from being able to bench mark industry's current capabilities. The aeromedical fraternity are only too familiar with upper spine and neck injuries to pilots wearing 'unadorned' helmets in modern fast-jets caused by the high positive accelerations (g_z) and high onset rates. A strong emphasis was therefore given to all up mass, even for limited trials flying.

Considerable experience has been gained flying NVGs. In enhancing the FOV from the 30° of earlier versions to the 40° of more recent types, significant improvements were gained both in performance and subjective ease of use. It was considered in the opinion of the technical contributors to the specification that to reduce the FOV available would be a retrograde step and unacceptable to pilots used to a wide FOV device.

The brightness and contrast requirements for all modes of operation, ie day and night flying, demanded high performance devices and efficient optical design. The high transmissibility requirement ensures that the normal view to the outside world would not be degraded in the interest of display legibility (brightness/contrast).

The experience gained in conducting this programme will provide the UK MOD with many benefits. Procuring the helmet will provide a measure of industry's current capability, flying the AIAH will be beneficial in building expertise in the human engineering and human factors associated with these devices, and operating with the helmet in a realistic environment will enable a raft of knowledge to be built up which will help establish operational techniques for the Integrated Helmet equipped pilots of the future.

8. REFERENCES

Ref 1 D N Jarrett and A Karavis, "Integrated Flying Helmets" *in* "The Man-Machine Interface in Civil and Military Aircraft" Institute of Mechanical Engineers Seminar, October 1991, Paper 4.

Fig. 1 Mk 10 ALPHA Helmet

Fig. 2 Alpha Helmet-Mounted Sight

Fig. 3
Monocular Helmet-Mounted Display

Fig. 4
Binocular Helmet-Mounted Display

Fig. 5 Night Vision Goggles

Multi-Function Visor

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1 INTRODUCTION

1.1 Traditional Roles

The primary role of aircrew visors has always been to provide facial protection in the event of ejection, bird strike or other hazards. It must achieve this with negligible degradation to normal vision, i.e. very high transmission, minimal colouration, minimal optical distortion. The material used is inevitably polycarbonate, which combines high mechanical strength with good optical qualities.

A secondary visor role has traditionally been to provide optical protection against solar glare. This is achieved by providing a dyed visor which gives relatively low transmission (10-20%) uniformly across the visible band. These sun visors must provide excellent protection against ultra-violet exposure and to a lesser extent against near Infra Red exposure. Similar requirements on mechanical and ophthalmic performance apply. The sun visor can be used instead of a clear visor or in conjunction with a clear visor. The twin visor system ensures that the mechanical protection of the clear visor is always present whilst the deployment of the sun-visor is optional, at the expense of additional weight. This is the approach currently adopted by the U.K.

1.2 Optical Threats

More recently additional protective requirements have evolved, which may also need to be incorporated into the visor. These are the threats to the pilot's vision posed by either lasers or the flash from a nuclear explosion.

The threat from lasers may be at Dazzle or Damage levels. Dazzle threats are typically c.w. lasers at relatively low powers, but which would cause temporary flash-blindness and would preclude viewing in the source direction.

These threats can typically arise over a wide band of wavelengths and active measures to counter them must respond in milliseconds.

Damage threats are posed by high power pulsed lasers and may cause permanent blindness in both eyes. Active measures to counter these must respond within a fraction of the timescale of the pulse (typically nanoseconds). These threats are primarily limited to a number of specific wavelengths corresponding to high efficiency pulsed lasers. They can therefore be countered by permanent fixed-line rejection filters at the relevant wavelengths.

Nuclear flash threats occur at ranges where the explosion is survivable but the intensity of the visible component of the flash is sufficient to pose hazards ranging from severe flash-blindness to permanent eye damage. Protection must be provided across the entire visible band, typically in a timescale of milliseconds.

1.3 Why Visors?

Ocular protection against these threats could be provided in a number of formats, for example spectacles or goggles or even integrated into the canopy. However, all such protection will carry a penalty in terms of normal visual transmission.

This will be discussed in more detail later. Where there is a permanent transmission loss associated with the protective device it is vital that a "look-past" capability be retained so the pilot can assess the relative importance of protection or transmission at any given time versus other threats which may be present and deploy the device accordingly.

The optimum format for this protection is therefore the aircrew visor, which can be rapidly and safely moved in and out of the field of vision.

1.4 HMD Combiners

Finally, a further role for the modern aircrew visor, is to function as the combiner in a Helmet Mounted Display system. In any such system the combiner must be located in front of the eyes and fixed to the helmet. There are systems with separate combiners located inside the visor, but these pose serious weight and safety problems. The most practical solution is to use the visor itself as the system combiner by providing suitable spectrally selective filters at the visor surface.

1.5 Multi-Function Visors

The role of visors in future cockpits is therefore greatly expanded. Each of these requirements cannot be met with a separate visor since the overall weight of the helmet assembly is also critical, especially in high-g aircraft. Ideally all of these requirements would be met with a single visor, or at most a pair of visors. This gives rise to the concept of the Multi-Function Visor (MFV).

A single visor that meets the full range of all of these requirements, with good transmission, is probably not a feasible concept. This is especially true for the protection against numerous laser lines in the visible band. However, what can be achieved are visors offering combinations of these requirements whilst still retaining an acceptably high transmission. The concept therefore is a suite of Multi-Function Visors, all meeting some basic requirements and offering different protective combinations on a mission-selective basis.

This presentation will very briefly survey the technologies available to meet these requirements, highlighting the effects on transmission. The application of these technologies to visors will be assessed and some of the work to date at Pilkington Optronics will be reported.

Finally the combination of these technologies to meet the Multi-Function Visor requirements will be addressed.

A summary of the requirements and constraints for Multi-Function Visors is shown in Figure 1.

2 TECHNOLOGIES

2.1 Moulding Technology

Injection moulded polycarbonate visors are currently the only way of achieving the necessary mechanical performance with good optical quality.

Polycarbonate is inherently soft so the exposed surfaces must be protected with an anti-scratch coating.

All additives (e.g. dyes) or surface processes must be such that they do not reduce the mechanical performance of the polycarbonate.

The optical/ophthalmic quality of the visor is primarily determined by the design and surface finish of the moulding tool and the control of the moulding process. The visor strength is enhanced if drilling and edging operations are avoided by moulding to final shape.

2.2 Absorption Technologies

The transmission characteristics of an optical component can be modified by incorporating selective absorbing materials within it. These are two major classes of absorbent materials: absorbing glasses and organic dyes. Glass materials are not suitable for use in visors, on mechanical and weight grounds.

Dyes (primarily organic dyes) can be incorporated into the polycarbonate prior to moulding, or in some cases can be imbibed into moulded components. The spectral properties of known dyes vary from broad-band to narrow-band, across the U.V. and visible spectrum. The available choice diminishes in the NIR.

To survive moulding in polycarbonate, the dyes must withstand high temperatures. Most organic dyes show some degree of solar degradation on long term exposure. Many organic dyes saturate if illuminated intensely at one wavelength (e.g. with a laser).

There are some very narrow band absorbing dyes available, but even these have leading and trailing absorption edges which significantly reduce the overall visual band transmittance.

2.3 Reflection Technologies

Specific wavelengths or wavelength bands, can be selectively reflected by the use of interference films. Transmission levels at given wavelengths can be reduced to 0.01% (OD4) or lower. The interference films can be in the form of holographic filters or multi-layer vacuum coatings. These can be designed to give very sharp spectral characteristics and to operate at any given wavelength. Combinations of such filters can reflect multiple wavelengths across the spectrum. Until recently it has been very difficult to apply these technologies to large, highly curved, polycarbonate visors.

The traditional holographic material, Dichromated Gelatin or DCG is degraded by water vapour and must be protected by glass. However, new holographic materials are more durable and have been successfully applied to large polycarbonate substrates.

Traditional techniques in vacuum coating are unable to deposit complex multi-layer coatings with sufficient uniformity across large, curved visors. Recent developments, notably at Pilkington Optronics, have overcome this. Similarly, mismatch problems between the visor material and typical coating materials have been overcome to ensure good environmental stability.

There is still one very fundamental limitation on the application of interference technologies to provide protective reflection. The spectral performance of all interference filters is dependent on the incidence angle of the light. At high angles the reflection is shifted to shorter wavelengths. To maintain reflectivity at a specific wavelength, over a wide range of incidence angles, the spectral width of the reflection filter must be extended. This reduces the transmission.

For optical threats in the Red or NIR the filter can be extended without significant loss of visual transmission, but for threats within the visual band the loss in transmission can be severe.

The angular coverage required to provide good optical protection is therefore a critical parameter in the design of protective interference filters. Pilkington Optronics have devised a series of computer models to accurately determine this for a wide range of devices, including visors.

The angular coverage required depends on the shape and curvature of the substrate or visor. Very highly curved visors, matched to the eye rotation curve, require the minimum angular coverage and therefore could have the highest transmission. Such visors are, however, impractical. Using holography, a technique can be adopted where the construction geometry is designed so that the effective shape of the filter does not follow the shape of the substrate it is deposited on. This is known as Non-Conformal Holography. This offers the possibility of good angular coverage and good transmission on a traditional visor shape and is currently an active area of development.

2.4 Active Technologies

The technologies described so far have all been passive, i.e. their spectral performance is fixed. There are a wide range of active filter technologies, where the spectral characteristics are modified in response to the incident radiation. It is not possible to do justice to this range in such a brief paper. However, most of these technologies are in the form of devices, with requirements for detectors, applied voltages, associated electronics or focussing optics. In general, they offer a limited aperture or limited field of view and would probably be used in a goggle format. The exception to this is photochromic technology, which requires no external components and offers excellent prospects for incorporation into multi-function visors. I will therefore concentrate solely on photochromic dyes.

Photochromic dyes darken under appropriate illumination and are well known in the form of sun-glasses. Pilkington are world leaders in the development of photochromic technology and the latest generation of dyes offer exceptional switching speeds, good optical densities and good coverage across the visual spectrum.

The dyes function by absorbing near u.v. and blue light which modifies the molecular structure to create additional absorption bands in the visible spectrum. The dyes can respond in pico seconds (under pulsed laser illumination) and for millisecond illumination pulses the dye response exactly follows the incident pulse-shape.

These dyes can be used for both active sun-visors and nuclear flash protection. The amount of u.v./blue light transmitted through aircraft canopies is sufficient to trigger the photochromic response.

The dyes can be incorporated into a range of polymer host materials, but unfortunately not polycarbonate.

Utilising these technologies, a number of optimised solutions to the Multi Function Visor Problem can be produced, each depending largely upon the priority given to the various functions the visor must perform.

3 MULTI-FUNCTION VISOR DESIGNS

3.1 MFV 1 - Solar/Laser Protection (low transmission)

One obvious multi-function visor approach is to use combinations of narrow band laser absorbing dyes in a visor, tailored to ensure the overall visual transmittance is at the 10-20° solar protection level. This sun-visor then provides laser protection at a number of discrete lines. With the dyes incorporated into polycarbonate these visors also meet all the ophthalmic and mechanical requirements.

This approach has been successfully adopted to provide 2-line and 3-line laser protection visors. With the appropriate selection of dyes, the colouration can be reasonably neutral, with excellent u.v./blue blocking and good NIR attenuation. There are limits on the number of laser lines that can be blocked whilst maintaining adequate transmission.

3.2 MFV 2 - Solar/Nuclear Flash/Laser Protection (moderate transmission)

The MFV 2 design is only suitable for daytime laser protection. For night time use the laser protection must be provided by combinations of vacuum coatings, non-conformal holograms (and possibly some narrow-band dyes). The optimum designs must provide high transmission, typically in excess of 50%. This can be achieved with coverage over perhaps 3-7 laser lines, depending on the precise choice of wavelengths.

Photochromic dyes can be incorporated into the visor to provide solar glare protection for daytime use. With the appropriate mix and concentrations of dye, the visor transmission will respond to ambient illumination levels and provide a more adaptable form of protection than the current sun-visors.

The intention is that the same photochromic dyes will also provide protection against nuclear flash. There will need to be a compromise between the optimum dye mix for nuclear flash protection and that for solar protection and the optimum concentrations are currently being investigated.

The transmission value for MFV 2 depends on the precise combinations of laser lines. Protection against lasers at the centre of the photopic eye response, or on the short wavelength side of it (for interference filters), results in a greater loss of visual transmission. In combining protective filters, care must also be taken to ensure that acceptable colour balance is maintained. In particular, it is vital that large sections of the visible spectrum are not blocked (for example "blue") since this will degrade colour discrimination.

Another vital parameter is display compatibility, especially with narrow band phosphors in Head-Up and Head-Down displays and with various shades of panel display and warning lights.

In reality, the full range of potential laser threats in the visible band cannot be covered on a single visor whilst maintaining adequate visual transmittance and colour balance. There will need to be a suite of MFV 2 visors offering different combinations of laser protection, all with photochromic solar and nuclear flash protection, all with U.V. and NIR protection. The choice of appropriate visor will be made on a mission by mission basis.

3.3 MFV 3 - HMD Combiner/Mechanical Protection

The one aspect not covered in the MFV 2 visor is the HMD combiner. This will typically be a very narrow band, non-conformal holographic filter providing high reflectivity over the limited range of angles required for the HMD system. In addition it will almost certainly need to supply some of the aberration correction for the overall system and will therefore be a complex hologram to construct.

In principle, this could be included in the MFV 2 visor with little degradation in overall transmittance. However, the MFV 2 visor will have limited visual transmittance and it is regarded as vital that the pilot retains a "look-past" capability by pushing this visor up, out the field of view. This would not be possible if it functions as the HMD combiner.

The proposed solution therefore requires a twin visor system. An inner clear visor with the HMD combiner, which is permanently down and an outer Multi-Function Visor whose deployment is controlled by the pilot. The inner visor will have very high visual transmittance and will provide full mechanical protection.

The outer visor will have limited visual transmittance (depending on the multi-functions) and need not provide full mechanical protection. The weight of the outer visor can therefore be reduced.

4 SUMMARY

A multitude of new roles are required for future aircrew visors. Large numbers of visors on a single helmet is not an acceptable solution. There is therefore a requirement for Multi-Function Visors which perform numerous roles.

Many of the optical protective functions carry an unavoidable loss of visual transmittance. When these are combined, the overall visual transmittance may typically be 40% or lower. These functions therefore need to be combined on an outer Multi-Function Visor which the pilot can deploy at will. A permanent inner clear visor will provide all the mechanical protection and will also host the HMD combiner.

A suite of outer MFV's may be required to cover all the combinations of laser threats in the visible, with the appropriate visor being selected for each mission.

5 ACKNOWLEDGEMENTS

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ADVANCES IN SPEECH PROCESSING

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1. Introduction

After almost three scores of years of basic and applied research, the field of speech processing is, at present, undergoing a rapid growth in terms of both performance and applications and this is fuelled by the advances being made in the areas of microelectronics, computation and algorithm design. Speech processing relates to three aspects of voice communications [1]:

- -Speech Coding and transmission which is mainly concerned with man-to-man voice communication.
- -Speech Synthesis which deals with machine-to-man communication.
- -Speech Recognition which is related to man-to-machine communication.

The paper first discusses the use of voice for civil and military communications and considers its advantages and disadvantages including the effects of environmental factors such as acoustic and electrical noise and interference and propagation. The structure of the existing NATO communications network and the evolving Integrated Services Digital Network (ISDN) concept is briefly reviewed to show how they meet the present and future requirements. It is concluded that speech coding at low-bit rates is a growing need for transmitting speech messages with a high level of security and reliability over capacity limited channels and for memory-efficient systems for voice storage, voice response, and voice mail etc. Furthermore it is pointed out that the low-bit rate speech coding can ease the transition to sharerl channels for voice and data and can readily adopt voice messages for packet switching.

The paper then deals with the fundamental subject of speech coding and compression. Recent advances in techniques and algorithms for speech coding now permit high quality voice reproduction at remarkably low bit rates. The advent of powerful single-chip signal processors has made it cost effective to implement these new and sophisticated speech coding algorithms for many important applications in voice communication and storage.

The subject of speech synthesis is next treated where the principal objective is to produce natural quality synthetic speech from unrestricted text input. Useful applications of speech synthesis include announcement machines (e.g. weather, time)computer answer back (voice messages, prompts), information retrieval from databases(stock price quotations, bank balances) reading aids for the blind, and speaking aids for the vocally handicapped.

Probably the most intractable of all the speech processing techniques which is last discussed in the paper is speech recognition where the ultimate objective is to produce a machine which would understand conversational speech with unrestricted vocabulary, from essentially any talker. Algorithms for speech recognition can be characterized broadly as pattern recognition approaches and acoustic phonetic approaches. To date, the greatest degree of success in speech recognition has been obtained using pattern recognition paradigms. It is for this reason that the paper is concerned primarily with this technique.

There are two distinct classes of signal. There are signals in time such as speech or music; and there are signals in space, like print, stone inscription, punched cards, and pictures. Out of all these communication forms, "'speech" is perhaps, the most "natural" mode by which human beings communicate with each other. There are also good reasons for people wishing to use speech to communicate with machines. it must, however, be pointed out that there is not much empirical evidence to show the value of speech over other modes of communication.

In a recent study carried out by the author [2] it was established that in a tri-service strategic C3I environment about half of the total traffic in Erlangs was for voice and the rest was approximately equally divided between data and message traffic. In an information theoretic sense, however, the bulk of communication was carried by the message handling system. About 70% of the traffic was for air operations. It is, however, expected that these proportions will change with time in favour of the data traffic. The traffic situation is, of course, very different in the civil network where, at least in the foreseeable future, voice service will continue to predominate all others. It must be stated however, that the main reason for the preponderance of message traffic in military networks today is the requirement of "recording" information in a secure and easily accessible way and ability to coordinate and disseminate it.

Notwithstanding the above, an experiment carried out at Johns Hopkins University [3] showed that teams of people interacting together to solve problems solved them much faster using voice than any other mode of communication. There are other studies which indicate that voice provides advantages over other means of communication for certain applications. There is no doubt that the main reason for the preference of voice, at least for certain applications, stems from it being "natural", not requiring any special training to learn, and freeing the hands and eyes for other tasks.

The features of speech communications that are disadvantageous relate to the difficulty of keeping permanent secure records, interference caused by competing environmental acoustic noise, physical psychological changes in the speaker causing changes in speech characteristics or disabilities of speaking/hearing and finallv its serial and

informal nature leading to slower information transfer and or information access. It must be pointed out however that some of the disadvantages of speech communication are dependent on the state of technology and can therefore change with time and application.

Fig.1 shows how the importance of the communication node changes with the phases of an engineering project [4]. The importance of text dominates at the beginning and end of an engineering development process. In the middle of the process, other forms of communication modes rise and fall in importance, due to the specialised design and implementation methods of engineering. Graphics maintains its importance throughout the process.

From the example above it is not too difficult to see a certain degree of resemblance between the modes of communication required for an engineering development project and those for command and control; all modes are required in general with preference given to some depending on application and the development of technologies and operational concepts.

2. COMMUNICATIONS NETWORKS

Because of the preponderance of traffic related to Air Operations in military networks we shall now take a brief look at the type of communications these operations require and the type of environment in which they are to work. Air operations involve both fixed and mobile platforms (land, sea and air) and communications that are required to interconnect them consist of:

- A switched terrestrial network
- Air/ground communications and
- intra-aircraft (cockpit) communications.

These communications are used to support:

- the management of offensive air operations
- the management of defensive aircraft
- regional, sub-regional air defence control systems.

in addition there are also dedicated communications employed for sustained surveillance, navigation and IFF.

The main air warfare missions and associated ranges together with the types of communications required are given in Fig.2. These communications are currently provided in NATO by a combination of international and national networks using both terrestrial and satellite links together with VHF/UHF ground/air, air/air and HF radio communications to and between tactical strategic aircraft (Fig. 3).

The terrestrial transmission systems used today provide nominally 4 kHz analogue circuits even though the NATO SATCOM systems is totally digitised and some national systems (PTT and military) use digital transmission links. NATO also owns and operates automatically switched voice and telegraph networks. It is to be noted that a significant portion of the traffic that flows in the common-user network is related to air operations. As far as UHF/VHF and HF radios are concerned, they provide analogue voice and data except for JTIDS (The Joint Tactical Information Distribution System) which is totally digital and is currently available for the NATO AEW program. The NATO communications systems carry so;me circuits which are cryptographically secure end-to-end and there are some links and circuits carried by SATCOM and JTIDS which are protected also against jamming.

2.1 Integrated Services Digital Network (ISDN)

NATO decided in 1984 that most of their terrestrial communications requirements would he met in the future by the strategic military communications networks, that are today being designed and some being implemented by the Member Countries. All these networks largely follow the CCITT IDN/ISDN standards and recommendations and adopt the International Standards Organisation's (ISO) Open System Interconnection Reference Model (OSI/RM). These digital common-user grid networks provide mission related, situation oriented, low-delay "teleservices" such as plain, secure voice, facsimile and non-interactive and interactive data communications. These are enhanced by "supplementary services" such as priority and pre-emption, secure/non-secure line warning as well as closed-user groups, call forwarding and others. The switching subsystem supports three types of connection methodology namely, semi-switched connections, circuit-switched connections, and packet/message switched connections. The circuit switching technique used is the byte-oriented, synchronous, time-division-multiplexed (TDM) switching in accordance with CCITT standards. The basic channels are connected through the network as transparent and isochronous circuit of 64 kb/s or nx64 kb/s where n is typically 32.

Future evolution of the ISDN will likely include the switching of broadband services at bit rates greater than 64 kb/s, at the primary rate, as well as switching at bit rates lower than 64 kb/s which are made possible by the end-to-end digital connectivity. Table 1 shows some typical service requirements for civil and also for military applications.

Table 1: Some Service Requirements

Service	Bandwidth Requirements	ISDN Channel Type B	D	Circuit Switched	Packet Switched	Channel Switched	/Overlay
*Telephone	8,16,32,64kb/s	x	x				
* Interactive Data Communications	4.8-64 kb/s	x		x	x		
*Electronic Mail	4.8-64 kbis	x			x		
*Bulk Data Trans.	4.8-64 kb/s	x		x			
* Facsimile/ Graphics	4.8-M kb/s	x		x			
*Slow Scan/ Freeze Frame TV	56-64 kb/s	x		x			
*Compressed Video Conference	1.5-2 Mb/s (Primary rate)					x	x

3. OPERATIONAL REQUIREMENTS

3.1 General

The requirements for air operations are subsumed in the total requirement for the switched networks. The network must be

dimensioned to meet the needs of non-mobile military traffic securely, reliably, survivably, and with no operationally significant delays, so as to preserve the radio-frequency spectrum for mobile and broadcast applications, including possibly the restoration or reconfiguration of the static network and/or rerouting of traffic following battle damage. The survivability of the communications must (at least) match that of the war headquarters and weapon sites which it integrates and serves. Operational procedures must be developed to maintain essential operation, even when the capacity of this network has been seriously reduced by battle damage. Survivability of connectivity is however the paramount importance.

The satellite network must similarly be dimensioned to meet the joint requirements of its total user community which comprises primarily those difficult to access otherwise because of:

a) Long range (and relatively large data-rate) requirements
b) mobility,
c) multi-access requirements.

Its security and ECM resistance must be assured and its potential any-to-any and any-to-all capability must be made available for flexible exploitation by the user.

Security and ECM resistance are equally required for the various tail links.

Air-ground and ground-air links for close fighter control cannot tolerate delays of more than a fraction of a second when they are part of a close-control loop. The true data-rate in information-theory terms, is not more than 100 bits. It is essential that the interface to the pilot will be user-friendly, and this should normally include (possibly synthesized) spoken messages, in order to keep the pilot's eyes free for his primary duties. Immunity to even short-term disruption by ECM is essential. The air-ground capacity required is marginally smaller than that for ground-air.

Broadcast Control can accept slightly longer delays, but it involves a more varied type of data and may involve a somewhat larger total data rate; it may also require more air-ground traffic. The need for communications with close-support strike aircraft, in a confused and rapidly changing battle situation are similar to those for fighters, but with increased flexibility and capacity in the air-ground direction.

Long-range deep-penetration missions must be accessible to relatively few and short re-targeting and recall messages. In principle,the data rates need to exceed a few bits per second, and delays of possibly several minutes could be tolerated if necessary. In the reply direction acknowledgements and reports of survival or otherwise, and of success or failure of a strike mission are equally undemanding in terms of communications capacity. Any reconnaissance reports from long range could also tolerate a delay of a few minutes if necessary, but even with data reduction, reconnaissance reports (from any range) can benefit from the widest bandwidth which can be provided with the technology available. For long-range missions, low probability of intercept would also be highly desirable.

If the technology dictates a sharp division in capability and/or solution between operations:

a) within line-of-sight from the ground behind the FEBA,
b) within line-of-sight from the air behind the FEBA,
c) beyond line-of-sight from the FEBA,

good, but distinct, solutions to these three scenarios can be accepted.

The operational requirements outlined above do certainly imply, in addition to graphic and data communications, the use of voice. Intelligibility is the most important parameter with "speaker recognition" aiding "authentication" being also required although its value in a multinational environment may be questioned.

3.2 Cockpit Engineering [5]

The basic piloting functions are the following:

- flying (control of aircraft manoeuvres)
- navigation (location and guidance)
- communications (voice and data link)
- utilities management
- mission management

Decisions to be made by the pilot related to the above tasks are crucially influenced by how information is obtained, and displayed and how communications are processed and handled. There is also the problem of language between the machine and the man. Even when the machine is as learned as the pilot, it will not always know what part of its knowledge is to be transmitted to the pilot or how to optimally transmit it.

It is generally accepted that in many current military aircraft, particularly single-crew aircraft, pilot workload is excessive and can be a limit to the capability of the aircraft as an operational weapon system. Advances in on-board avionics systems have the potential for generating more information, and considerable care will be required in optimising the man-system interface in order that the human pilot capability (which will be essentially unchanged) is not a major constraint on overall system performance.

3 .3 The Use of Voice Systems in the Cockpit

Visual signals are spatially concerned; one needs to direct the field-of-view, moreover, in high workload phases of the mission, attention can be focused on some types of cisual information such that other information which suddenly becomes important can be "overloaded". Also the amount of information may saturate the visual channel capacity. Aural signals have the advantage of being absorbed independently of visual engagement, while man's information acquisition capacity is increased by using the two channels simultaneously. Motoric skills are hardly affected by speaking. For information being sent from aircraft to other humans on the ground and in the air, speech is a natural and efficient technique which has been used for many years. Until now the process of aural communication between aircrew and systems has been usually restricted to a limited range of warning signals generated by the systems.

Digital voice synthesis devices are now widely available and have many commercial applications. Technically there appear to be no problems in using them in aircraft to transfer data from aircraft systems to aircrew, the real difficulty being in identifying the types of message which are best suited to this technique. Warning messages currently appear to be a particularly useful application, though these will probably need to be reinforced by visual warnings as aircrew can totally miss aural warnings under some conditions. Feedback of simple numerical data is also being considered.

One of the main disadvantages of aural signals is that the intelligibility is greatly impaired by noise in the cockpit; this is true both ways. However, the understanding of the mechanisms of speech synthesis and speech recognition has reached the point where voice systems in the cockpit can be considered. Although electronic voice recognition in the laboratory reaches scores of 96 to 98% (comparable with keyboard inputs) the vocabulary: is still very limited and recognition tends to be personalised. But the prospect of logic manipulation in AI techniques can greatly improve the situation to depersonalise recognition in noisy environments. Actual data on such improvements are difficult to contain. These would also depend on how much redundancy is used in both syntax and semantics.Furthermore a coding "language" is to be preferred just as in conventional aircraft radio communication, to prevent the system responding to unvoluntarily uttered (emotional) exclamations.

Several commercial voice recognition equipments are currently available on the open market, but many of these have not been designed for airborne application and considerable development will be needed before they can be regarded as usable equipments for combat aircraft. Simulator and airborne trials in a number of countries using this early equipment have identified the following as key areas in which further investigation/improvement is required:

a) Size of vocabulary. At present this is very limited, but recognition performance is generally inversely related to vocabulary size.

b) Background noise distortion. The cockpit environment is frequently very poor, and the oxygen mask and microphone are far from ideal.

c) Necessity for pre-loading voice signatures. Current systems have to be loaded with individual voice templates. Consequently, if aircrew voice changes (e.g.. under stress) recognition performance is reduced. Moreover some subjects have a much greater natural variability in their voices than others.

d) Continuous speech recognition. Most early equipments can only recognise isolated words, whereas in natural speech the speaker frequently allows one word to flow continuously into the next.

e) Recognition Performance. Even under ideal conditions, recognition scores are always less than 100% and under bad conditions and with poor objects the scores may be only 50-75%c. Thus it is currently necessary and probably will continue to be so-to have some form of feedback to confirm to the speaker that the message has been correctly captured.

In ummary, trials with first generation voice recognition equipments bave produced encouraging results, but the need for significant improvements has been identified and these are now being explored. It may be too early to give an exact estimate of the extent to which voice recognition techniques will be used in future combat aircraft, but there is considerable promise that a valuable new interface channel can be developed. First applications are likely to be in areas where 100% accuracy in data transmission is not essential and where an alternative form of data input is also available to aircrew.

4. SPEECH PROCESSING

4.1 General

Having established the fact that the spoken word plays and will continue to play a significant role in man-man, man-machine and machine-man communications for civil and military applications both real-time and with intermediate storage (e.g., for "voice mail") a brief look will now be taken at the developments in speech processing that contribute significantly in all these areas.

Fig 4 shows roughly the relationship between speech transmission and recognition and synthesis of speech [6]. In each case processing starts with "preprocessing" which extracts some important signal characteristics. The following stage which is still a preprocessing stage but extracts more complicated and combinatorial parameters such as segmented phoneme parameters or prosodic parameters like speech intonation which are necessary for a speech recognition system. The succeeding stages are concerned with the central issue of recognition and understanding. A speech output is then produced based on linguistic rules. The phonetic and speech synthesis parts again handle the higher and lower level parameters to produce a speech signal which, when applied to a loudspeaker/earpiece, is converted into an acoustic signal. In a speech transmission system with redundancy reduction (compression), the inner part of Fig 4 is by-passed and a parametric description of the analyzed signal is directly sent to a synthesizer which can reproduce the speech signal.

4.2 Speech Coding

Speech compression systems can generally be classified as either Waveform Coders or Vocoders, (i.e., voice coders or analysis-synthesis telephony).These two classes cover the whole range of compressibility from 64000 down to a few hundred bits per second. The important factors which need to be taken into account when comparing different encoding techniques are the speech quality achievable in the presence of both transmission errors and acoustic noise, the data rate required for transmission, the delay introduced by processing, the physical size of the equipment and the cost of implementation (a function of coder complexity which can be measured by the oumber of multiply-add operations required to code speech, usually expressed in millions of instructions per second "MIPS").

The most basic type of waveform coding is pulse code modulation (PCM) consisting of sampling (usually at 8 kHz),

quantising to a finite number of levels, and binary encoding.

There are many variations on the basic PCM idea, the most common being differential encoding and adaptive quantisation. Each variation has the object of recuding the data rate required for a given speech quality, a saving of approximately 1 bit per sample (kbit/s) being achieved when each is optimally employed. In differential PCM (DPCM) the sampled speech signal is compared with a locally decoded version of the previous sample sample prior to quantisation so that the transmitted signal is the quantised difference between samples. In adaptive PCM (APCM) the quantiser gain is adjusted to the prevailing signal amplitude, either on a short term basis or syllabi cally. By controlling the adaption logic from the quantiser output, the quantiser gain can be recovered at the receiver without the need for additional information to be transmitted. Adaptive differential PCM (ADPCM) is a combination of DPCM and APCM which saves 2 to 4 bits per sample compared with PCM, thus giving 48 to 32 kb/s high quality speech.

There is another adaptive approach to producing high quality and lower bit-rate coder which is called "adaptive subband coding" which divides the speech band into four or more contiguous bands by a bank of filters and codes each band using APCM. After lowering the sampling rates in each band, an overall bit rate can be obtained while maintaining speech quality; by reducing the bits/sample in less perceptually important high-frequency bands. Bands with low energy use small step sizes, producing less quantisation noise that with less flexible systems. Furthermore, noise from one band does not affect other frequency bands. Coders operating at 16 kb/s using this technique have been shown to give high quality but with high complexity [7].

When the number of quantization levels in DPCM is reduced to two, delta modulation (DM) results. The sampling frequency in this case is equal to the data rate, but it has to be above the nyquist frequency to ensure that the binary quantization of the difference signal does not produce excessive quantisation noise.Just as with PCM, there are many variations of DM. The most important from of DM used in digital speech communications is syllabically companded DM; there are a number of closely related versions of this, examples being continuously variable slope DM (CVSD) and digitally controlled DM (DCDM). The data rate requirements are a minimum of about 16 kb/s for military tactical quality speech and about 48 kb/s for commercial quality.

When operated at data rates of 12 kbit/s and lower, the speech quality obtained with PCM and DM coders is poor, and consequently they cannot be used as narrow band devices.

Analysis-synthesis telephony techniques are based on a model of speech production. Briefly, these are vocal tract running from the vocal chords at the top of the larynx to the mouth opening at the lips, and the nasal tract branching off the vocal tract at the velum and running to the nose opening at the nostrils. The glottis (the space between the vocal chords) and the sub-glottal air pressure from the lungs together regulate the flow of air into the vocal tract, and the velum regulates the degree of coupling between the vocal and nasal tracts (i.e., the nasalisation).

There are two basic types of speech sound which can be produced, namely voiced and unvoiced sounds. Voiced sounds occur when the vocal chords are tightened in such a way that the subglottal air pressure forces them to open and close quasi-periodically, thereby generating "puffs"of air which acoustically excite the vocal cavities. The pitch of voiced sounds is simply the frequency at which the vocal chords vibrate. On the other hand, unvoiced sounds are produced by forced air turbulence at a poind of constriction in the vocal tract, giving rise to a noise-like excitation, or "hiss".

In channel vocoding the speech is analyzed by processing through a bank of parallel band-pass filters, and the speech amplitude in each frequency band is digitized using PCM techniques. For synthesis, the vocal and nasal tracts are represented by a set of controlled gain, lossy resonators, and either pulses or white noise are used to excite them. In pitch-excited vocoders, the excitation is explicitly derived in the analysis, whereas in voice-excited vocoders it is derived by non-linear processing of the speech signal in a few of the low frequency channels combined into one. Pitch-excited vocoders require data rates in the range from 1200 bit/s to 2400 bit/s and yield poor quality speech, whereas voice-excited vocoders will provide reasonable speech quality at 4800 bit/s and good quality at 9600 bit/s.

A formant vocoder is similar to a channel vocoder, but has the fixed filters replaced by formant tracking filters. The centre frequencies of these filters along with the corresponding speech formant amplitudes are the transmitted parameters. The main problems in acquiring and maintaining lock on the relevant spectral peaks during vowel-consonant-vowel transitions, and also during periods where the formants become ill-defined. The data rate required for formant vocoders can be as low as 600 bit/s, but the speech quality is poor. The minimum data rate required to achieve good quality speech is about 1200 bit/s, but to date this result has only been obtained using semi-automated analysis with manually interpolated and corrected formant tracks.

The third method of analysis-synthesis telephony to have achieved importance is linear predictive coding(LPC). In this technique the parameters of a linearised speech production model are estimated using mean-square error minimisation procedures. The parameters estimated are not acoustic ones as in channel and formant vocoders, but articulatory ones related to the shape of the vocal tract. For a given speech quality, a transmission data rate reduction in comparison with acoustic parameter vocoding should be achieved because of the lower redundancy present. Just as with channel and formant vocoders, excitation for the synthesizer has to be derived from a separate analysis, the usual terminology being pitch-excited or residual excited, corresponding to pitch or voice excitation in a channel vocoder. LPC is a very active area of speech research, and new results appear regularly. At present data rates as low as 2400 bit/s have been achieved for pitch-excited LPC with reasonable quality speech, and in the range from 8 kbit/s to 16 kbit/s for residual excited LPC with good speech quality.

The application of vector quantisation (VQ), a fairly new direction in source coding, has allowed LPC rates to be dramatically reduced to 800 b/s with very slight reduction in

quality, and further compressed to rates as low as 150 b/s while retaining intelligibility (8,9]. This technique consists of coding each set or vector of the LPC parameters as group instead of individually as in scalar quantisation. Vector quantisation can be used also for waveform coding.

A good candidate for coding at 8 kb!s is multipulse linear predictive coding, in which a suitable number of pulses are supplied as the excitation sequence for a speech segment-perhaps 10 pulses for a 10-ms segment. The amplitudes and locations of the pulses are optimised, pulse by pulse, in a closed-loop search. The bit rate reserved for the excitation information is more than half the total bit rate of 8 kb/s. This does not leave much for the linear predictive filter information, but with VQ the coding of the predictive parameters can be made accurate enough.

For 4 kb/s coding, code excited or stochastically excited linear predictive coding is promising. The coder stores a repertory of candidate excitations, each a stochastic, or random sequence of pulses. The best sequence is selected by a closedloop search. Vector quantization in the linear predictive filter is almost a necessity here to guarantee that enough bits are available for the excitation and prediction parameters. Vector quantization ensures good quality by allowing enough candidates in the excitation and filter codebooks.

Table II below compares tradeoffs for representative types of speech coding algorithms [10].It shows the best overall match between complexity, bitrate and quality. A coder type is not necessarily limited to the bit rate stated. For example, the medium-complexity adaptive differential pulse-code modulation coder can be redesigned to give communication-quality speech at 16 kb/s instead of high-quality speech at 32 kb/s. In fact, a highly complex version can provide high-quality speech at the lower bit rate. Similarly lower-complexity multipulse linear predictive coding can yield high-quality coding at 16 kb/s, and a lower-complexity stochastically excited linear predictive coder (LPC) can be designed if the bit rate can be 8 kb/s instead of 4 kb/s.

Table II: Comparison Low Bit-Rate Speech Coding Schemes

Coder type	Bit rate kb/s	Complexity MIPS	Delay ms	Quality	MOS
*Pulse-code modulation	64	0.01	0	High	
*Adaptive differential pulse-code modulation	32	0.1	0	High	>4
*Adaptive subband coding	16	1	25	High	
*Multipulse linear predictive coding	8	10	35	Communication	
*Stoshastically excited linear predictive coding	4	100	35	Communication	>2
*LPC vocoder	2	1	35	Synthetic	<2

Cost is also a tradeoff factor, but it is hard to quantify in a table. The cost of coding hardware generally increases with complexity. However, advances in signal processor technology tend to decrease cost for a given level of complexity and, more significantly, to reduce the cost difference between low-complexity and high-complexity techniques.

Of course, as encoding and decoding algorithms become more complex they take longer to perform. Complex algorithms introduce delays between the time the speaker utters a sound and the time a coded version of it enters the transmission systems. These coding delays can be objectionable in two-way telephone conversations, especially when they are added to delays in the transmission network and combined with uncancelled echoes. Coding delay is not a problem if the coder is used in only one stage of coding and decoding, such as in voice storage. If the delay is objectionable because of uncancelled echoes the addition of an echo canceler to the voice coder can eliminate or mitigate the problems. Finally, coding delay is not a concern if the speech is merely stored in digital form for later delivery.

Many explanations can be given as to why particular types of speech coder do not perform well at low data rates. With waveform coders, it is generally accepted that the main reason is excessive quantisation noise despite companding and or adaptive logic. With analysis-synthesis techniques, the main reasons are over-simplification of the vocal tract model, leading to imprecise spectral characterization, and unreliable pitch detection and voiced-unvoiced-silence decisions in the analyzer which, coupled with an over-simplified excitation model in the synthesizer, lead to imprecise temporal characterisation and a lack of naturalness in the synthetic speech.

A quantitative description of the current state of telephone speech coding in terms of standards activity, bit rate, and MOS is summarized in Fig. 5. The solid curves in this figure refer to generic examples of coding algorithms outlined in the text above and the broken curve represents a research goal which is regarded as achievable. The solid dots refer to coding algorithms that provide high quality at 64,32 and 16 kb/s.

In conclusion on speech coding, it should be remarked that there are two complementary trends that are at work in digital telecommunications: speech coding developers are trying to reduce the bit rate for a given quality level while developers of modulation and demodulation techniques are endeavouring to encrease the bit rate that a channel of a given bandwith can accommodate.

4-3 Speech Synthesis

Speech synthesis involves the conversion of a command sequence or input text (words or sentences) into speech waveform using algorithms and previously coded speech data. The text can be entered by keyboard, optical character recognition, or from a previously stored data base. Speech synthesizer can be characterized by the size of the speech units they concatenate to yield the output speech as well as by the method used to code, store and synthesize the speech. Large speech units, such as phrases and sentences can give high-quality output speech (with large memory

requirements). Efficient coding methods reduce memory needs, but usually degrade speech quality.

Synthesizers can be divided into two classes: text-to-speech systems which constructively synthesize speech from text using small speech units and extensive linguistic processing, and voice response systems which reproduce speech directly from previously-coded speech, primarily using signal processing techniques. Voice response systems are often called "speech coders" and contain both an analyzer and a synthesizer.

Svnthesizers can also be classified by how they parametrize speech for storage and synthesis. High quality systems with large memory capacities synthesize speech by recreating the waveform sample-by-sample in the time domain. More efficient (but lower quality) systems attempt to recreate the frequency spectrum of the original speech from a parametric representation. A third possibility is direct simulation of the vocal tract movements using data derived from X-ray analysis of human production of specified sound sequences. Due to the difficulty of obtaining accurate three dimensional vocal tract representations modelling the system with a limited set of parameters, this last method usually yields lower quality speech and bas yet to have commercial application.

The simplest synthesizers concatenate stored words or phrases. This method yields high-quality speech (depending on the synthesis method) but is limited by the need to store in computer (read-only) memory all the phrases to be synthesized after they have been spoken either io isolation or in carrier sentences. For maximum naturalness in the synthetic speech, each word or phrase must originally be pronounced with timing and intonation appropriate for all sentences in which it could be used.

Hybrid synthesises concatenate intermediate-sized units of stored speech such as syllables, demisyllables, and diphones, using smoothing of special parameters at the boundaries between units. To further enhance the flexibilityof sto red-speech synthesis systems, ooe can allow control of prosody (pitch and duration adjustments) during the synthesis process. With the decreasing cost of digital storage, stored-speech synthesis techniques could provide low-cost voice output for many applications.

It is clear that stored-speech systems are not flexible enough to convert unrestricted English (or whatever language) text to speech. A text-to-speech system that uses synthesis-by rule is needed for applications such as accessing electronic mail by voice, a reading machine etc. The text-to-speech system must convert incoming text, such as electronic mail, that often includes abbreviations, Roman numerals, dates, times, formulas, and a wide variety of punctuation marks into some reasonable, standard form. The text must be further translated into a broad phonetic transcription.

There are several commercial text-to-speech conversion systems in the market which come in board, peripheral, software or system form. They are mostly for English adult male but some do adult female and child voice. The speech mode used is mostly words with some accepting also letters. The synthesis technique employed is mostly formant synthesis but some manufactures use LPC. Prices vary from a few hundred Dollars for software to a few tens of thousand Dollars for systems. The quality of even the best systems is such that during tests, listeners understood the synthetic speech produced 97.7% of the time compared with 99.4% tior human speech. Research in text-to speech synthesis which concentrates, at present, on producing speech that sounds more natural, is expected to provide systems which are more flexible for selecting the speaker characteristics, different languages and their dialects, and regional variabilities.

4.4 Speech Recognition [14]

Of all the speech processing techniques, speech recognition is the most intractable one. The ultimate objective of most research in this area is to produce a machine which would understand conversational speech with unrestricted vocabulary, from essentially any talker. We are far from this goal.

The reason why automatic speech recognition is such a difficult problem can be stated very briefly under four problem areas: First, the speech signal is normally continuous and there are no acoustic markers which identify the word boundaries. Second, speech signals are highly variable from person to person and even in one and the same person depending on his state. The third problem area is ambiguity which is characterised by conditions whereby patterns which should be different end up looking alike. The fourth problem area results from the fact that the speech signal is a part of the complex system of human language where it is often the intention behind a message that is more important than the message itself. Therefore an advanced speech recogniser would be expected to incorporate techniques which would enable it to use the meanings of words in order to interpret what bas been said. However, there are several applications which do not require this full capability. They range from voice editors, and information retrieval from data bases to basic English and large vocabulary systems required for office dictation/word processing and language translation.

A technology that is closely related to speech recognition is speaker recognition, or automatic recognition of a talker from measurements of individual characteristics in the voice signal. The two tasks that are relevant here are "absolute identification" and "talker verification" the former being the more difficult to perform. An interesting military application of speaker recognition is related to the monitoring of enemy radio channels with a view to identifying, perhaps in conjunction with keyword recognition, critical situations before they occur.

The recognition problem has at least three dimensions: vocabulary size, speaker identity and fluency of input speech and the performance of speech recogniser also depend on the acoustic environment and transmission conditions. Current understanding permits building practical systems that reliably recognise several hundred words spoken by a person who trained the system. Recognition for any or all speakers requires about ten times more computation than for individuals whose vocabulary patterns have been stored. Recognition of single words or short phrases-spoken in isola-

tion-can be done reliably, even over dialed-up telephone channels. Recognition of connected words is under active development. Recognition of conversational fluent speech is in fundamental research, and advances st. ·ngly depend on good computational models for syntax and semantics.

When setting out to define the problems associated with implementing a speech recognition system, one finds that there are a number of general issues that must be resolved before designing and building the system. One such issue is the size and complexity of the user vocabulary. Although useful recognition systems have been built with as few as two words (yes, no), there are at least four distinct ranges of vocabulary size of interest. Very small vocabularies (on the order of 10 words) are most useful for control tasks - e.g. all digit dialing of telephone numbers, repertory name dialing, access control etc. Generally the vocabulary words are chosen to be highly distinctive words (i.e. of low complexity) to minimize potential confusions. The next range of vocabulary size is moderate vocabulary systems having on the order of 100 words. Typical applications include spoken computer languages, voice editors, information retrieval from databases, controlled access via ~elling etc. For such applications, the vocabulary is general. irly complex (i.e. not all pairs of words are highly distinctive), but word confusions are often resolved by the syntax of the specific task to which the recognizer is applied. The third vocabulary range of interest is the large vocabulary s ystem with vocabulary sizes on the order of 1000 words. Vocabulary sizes this large are big enough to specify fairly comfortable subsets of English and hence are used for conversational types of applications - e.g. the IBM laser patent text, basic English, etc. [12,13]. Such vocabularies are inherently very complex and rely heavily on task syntax to resolve recognition ambiguities between similar sounding words. Finally the last range of vocabulary size is the very large vocabulary system with 10,000 words or more. Such large vocabulary sizes are required for office dictation/word processing and language translation applications.

Although vocabulary size and complexity is of paramount importance in specifying a speech recognition system, several other issues can also greatly affect the performance of a speech recognizer. The system designer must decide if the system is to be speaker trained, or speaker independent; the format for talking must be specified (e.g. isolated inputs, connected inputs, continuous discourse); the amount and type of syntactic and semantic information must be specified the speaking environment and transmission conditions must be considered etc. The above set of issues, by no means exhaustive, gives some idea as to how complicated it can be to talk about speech recognition by machine.

There are two general approaches to speech recognition by machine, the statistical pattern recognition approach, and the acoustic-phonetic approach. The statistical pattern recognition approach is based on the philosophy that if the system has "seen the pattern, or something close enough to it, before, it can recognize it." Thus, a fundamental element of the statistical pattern recognition approach is pattern training. The units being trained, be they phrases, words, or subword units, are essentially irrelevant, so long as a good training set is available, and a good pattern recognition model is applied. On the other hand, the acoustic-phonetic approach to speech recognition has the philosophy that speech sounds have certain invariant (acoustic) properties, and that if one could only discover these invariant properties, continuous speech could be decoded in a sequential manner (perhaps with delays of several sounds). Thus, the basic techniques of the acoustic-phonetic approach to speech recognition are feature analysis (i.e. measurement of the invariants of sounds), segmentation of the feature contours into consistent groups of features, and labelling of the segmented features so as to detect words, sentences, etc. To date, the greatest success in speech recognition have been achieved using the pattern recognition approach [14].

Figure 6 shows a block diagram of the pattern recognition model used for speech recognition. The input speech signal, s(n), is analyzed (based on some parametric model) to give the test pattern, T, and then compared to a prestored set of reference patterns, $\{R_v\}$, $1<v<V$ (corresponding to the V labelled ,patterns in the system) using a pattern classifier (i.e. a similarity procedure). The pattern similarity scores are then sent to a decision algorithm which, based upon the syntax and/or semantics of the task, chooses the best transcription of the input speech.

Results On Isolated Word Recognition

Using the pattern recognition model of Fig. 6 with an 8^{th} order LPC parametric representation, and using the non-parametric template approach for reference patterns, a wide variety of tests of the recognizer have been performed with isolated word inputs in both speaker dependent (SD) and speaker independent (SI) modes. Vocabulary sizes have ranged from as small as 10 words (i.e. the digits zero-nine) to as many as 1109 words.

Table III gives a summary of recognizer performance under the conditions discussed above. It can be seen that the resulting error rates are not strictly a function of vocabulary size, but also are dependent on vocabulary complexity. Thus a simple vocabulary of 200 polysyllabic Japanese city names had a 2.7% error rate (in an SD mode), whereas a complex vocabulary of 39 alphadigit terms (in both SD and SI modes) had error rates of on the order of 4.5 to 7.0%.

Table III also shows that in cases where the same vocabulary was used in both SD and SI modes (e.g. the alphadigits and the airline words), the recognizer gave reasonably comparable performances. This result indicates that the SI mode clustering analysis, which yielded the set of SI templates or models, was capable of providing the same degree of representation of each vocabulary word as either casual or robust training for the SD mode. Sometimes the computation of the SI mode recognizer was higher than that required for the SD mode whenever a larger number of templates were used in the pattern similarity comparison.

Table III: Performance of Template-Based Isolated Word Systems

Vocabulary	Mode	Error Rate (%)
10 Digits	SI	0.1
37 Dialer Words	SD	0
39 Alphadigits	SD	4.5
	SI	7.0
54 Computer Terms	SI	3.5
129 Airline Words	SD	1.0
	SI	2.9
200 Japanese Cities	SD	2.7
1109 Basic English	SD	4.3

Connected Word Recognition Model

Typical performance results for connected word recognizers, based on a level building implementation, are shown in Table IV. For a digits vocabulary, string accuracies greater than 99% have been obtained. For name retrieval, by spelling, from a 17,000 name directory, string accuracies of from 90%0 to 96% have been obtained. Finally, using a moderate size vocabulary of 127 words, the accuracy of sentences for obtaining information about airlines schedules is between 90% and 99%. Here the average sentence length was close to 10 words. Many of the errors occurred in sentences with long strings of digits.

Continuous, Large Vocabulary, Speech Recognition

The area of continuous, large vocabulary, speech recognition refers to systems with at least 1000 words in the vocabulary, a syntax approaching that of natural English (i.e. an average branching factor on the order of 100), and possibly a semantic model based on a given, well defined, task. For such a problem, there are three distinct sub-problems that must be solved, namely choice of a basic recognition unit (and a modelling technique to go with it), a method of mapping recognized units into words (or, more precisely, a method of scoring words from the recognition scores of individual word units), and a way of representing the fomal syntax of the recognition task (or, more precisely, a way of integrating the syntax directly into the recognition algorithm).

For each of the three parts of the continuous speech recognition problem, there are several alternative approaches. For the basic recognition unit, one could consider whole words, half syllables such as dyads, demisyllables, or diphones, or sound units as small as phonemes or phones. Whole word units, which are attractive because of our knowledge of how to handle them in connected environments, are today impractical to train since each word could appear in a broad variety of contexts. Therefore the amount of training required to capture all the types of word environments is unrealistic. For the sub-word units, the required training is extensive, but could be carried out using a variety of well known, existing training procedures. A full system would require between 1000 and 2000 half syllable speech units. For the phoneme-like units, only about 30-100 units would have to be trained.

The problem of representing vocabulary words, in terms of the chosen speech unit, has several possible solutions. One could create a network of linked word unit models for each vocabulary word. The network could be either a deterministic (fixed) or a stochastic structure. An alternative is to do lexical access from a dictionary in which all word pronunciation variants (and possibly part of speech information) are stored, along with a mapping from pronunciation units to speech representation units.

Finally the problem of representing the task syntax, and integrating it into the recognizer, has several solutions. The task syntax, or grammar, can be represented as a deterministic state diagram, as a stochastic model (e.g. a model of word trigram statistics), or as a formal grammar. There are advantages and disadvantages to each of these approaches.

To illustrate the state of the art in large vocabulary speech recognition, consider the results shown in Table V. The table shows results for two tasks, namely an office dictation system [15], and a naval resource management system [16-21]. The office dictation system uses phoneme-like units in a statistical model to represent words, where each phoneme-like unit is a statistical model based on vector-quantized spectral outputs of a speech spectrum analysis. A third statistical model is used to represent syntax; thus the recognition task is essentially a Bayesian optimization over a triply embedded sequence of statistical models. The computational requirements are very large, but a system has been implemented using isolated word inputs for the task of automatic transcription of office dictation. For a vocabulary of 5000 words, in a speaker trained mode, with 20 minutes of training for each talker, the average word error rates for 5 talkers are 2% for prerecorded speech, 3.1 % for read speech, and 5.7% for spontaneously spoken speech [14]. The naval resource management system also uses a set of about 2000 phoneme-like units (PLU's) to represent words where each PLU is a statistical model of a phoneme in specified contexts. The task syntax (that of a ships database) is specified in the form of a finite state network with a word pair grammar with average word branching factor (perplexity) of 60. When tested on a vocabulary of 991 words, in a speaker independent mode, using continuous, fluently spoken, sentences, a word error rate of about 4.5 % was obtained [20].

Summary

The challenges in speech recognition are many. As outlined above the performance of current systems is barely acceptable for large vocabulary systems, even with isolated word inputs speaker training, and favourable talking environment. Almost every aspect of continuous speech recognition, from training to systems implementation, represents a challenge in performance, reliability, and robustness.

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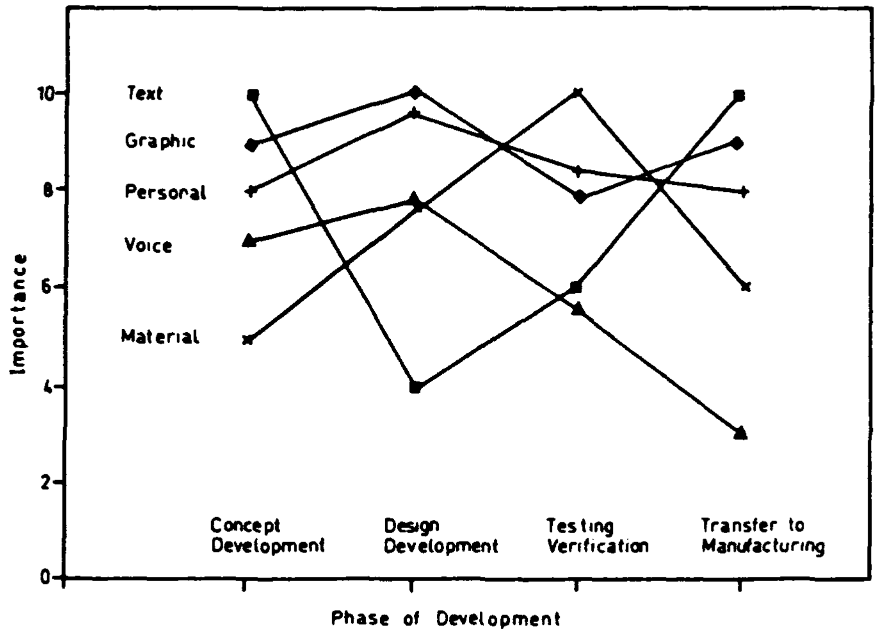

Fig.1. Encoding of Communications in an Engineering Development

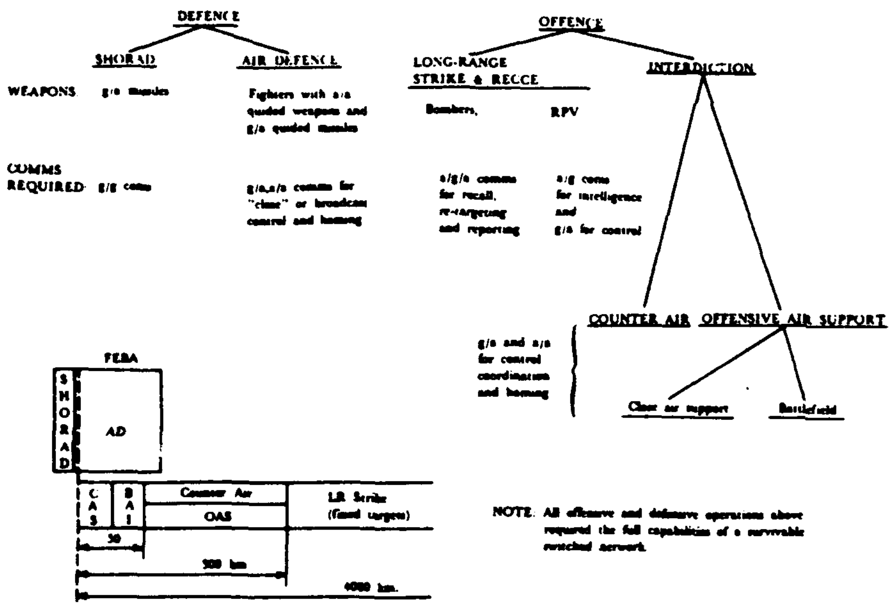

Fig.2. Air Warfare Missions and Range

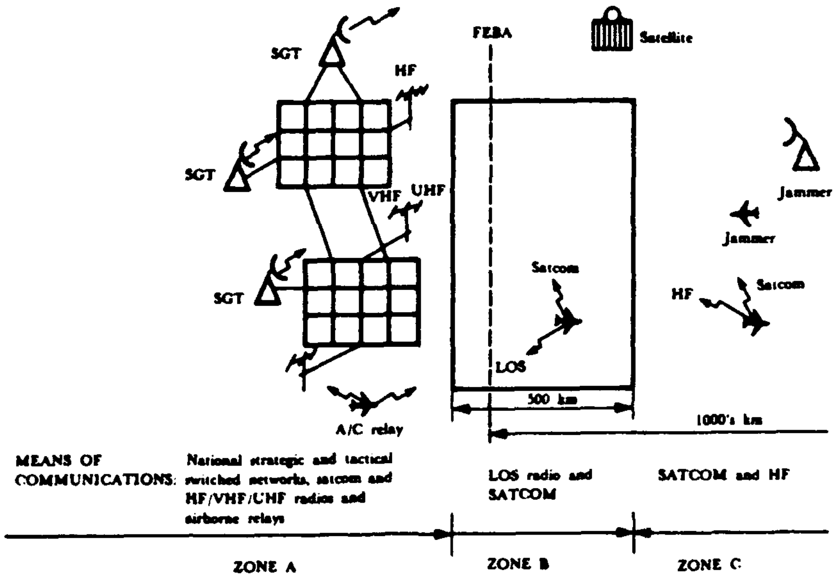

Fig.3. Communications Zones and Means

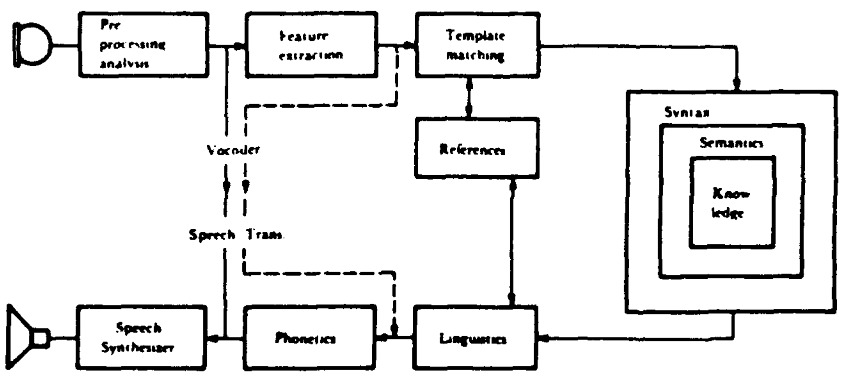

Fig.4. Relation Between Different Speech Bandwidth Compression and Coding Techniques [6]

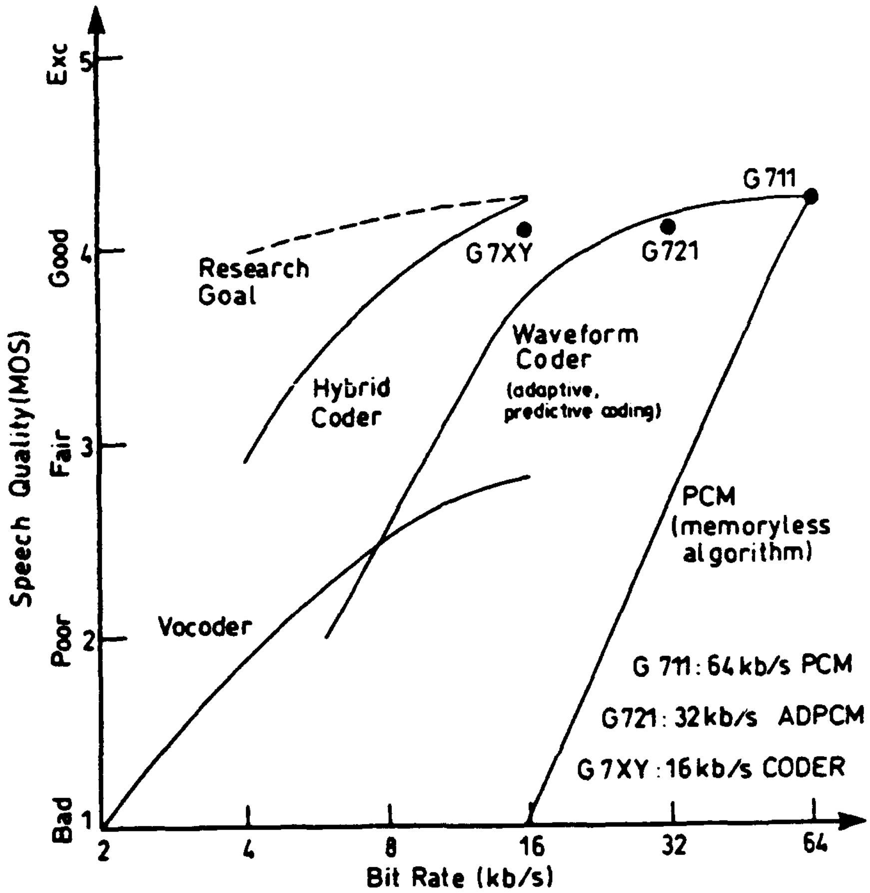

Fig.5. 3.2 kHz Speech Quality and Transmission Rate [11]

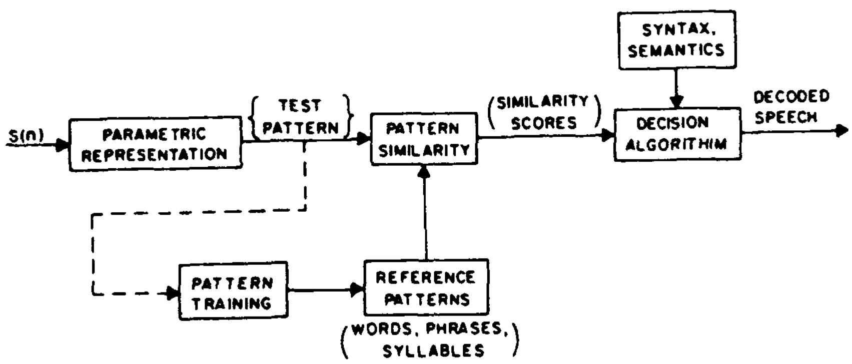

Figure 6. Pattern Recognition Model for Speech Recognition.

VOCABULARY	MODE	WORD ACCURACY	TASK	STRING (TASK) ACCURACY
Digits (10 words)	Speaker Dependent or Speaker Independent	99.8% SI	1-7 Digit Strings	99.2% SI*
		99.9% SD	1-7 Digit Strings	99.6% SD*
Letters of the Alphabet (26 words)	Speaker Dependent or Speaker Independent	≈ 90%	Directory Listing Retrieval (17,000 Name Directory)	96% SD 90% SI
Airline Terms (129 words)	Speaker Dependent or Speaker Independent	99.9% SD 97% SI	Airline Information and Reservations	99% SD 90% SI

* Known string length.

Table IV

Performance of Connected Word Recognizers on Specific Recognition Tasks

Task	Syntax	Mode	Vocabulary	Word Error Rate
Office Direction (IBM)	Word Trigram (Perplexity=100)	SD. Isolated Word Input	5000 Words	2%-prerecorded speech 3.1%-read speech 5.7%-spontaneous speech
Naval Resource Managements (DARPA)	Finite State Grammar (Perplexity=60)	SI. Fluent Speech Input	991 Words	4.5%

Table V
Performance of Large Vocabulary Speech Recognizers on Specific Recognition Tasks

THE USE OF VOICE PROCESSING FOR SOME ASPECTS OF THE PILOT-VEHICLE-INTERFACE IN AN AIRCRAFT.

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ABSTRACT

This paper describes the challenges that lie in the development and design of a pilot vehicle interface (PVI), both in the basic voice processing technologies as in the robustness requirements of the system, due to the peculiar circumstances in which it has to be used.
Furthermore, we will focus on the state of the art, and on the results of the current R&D efforts within Lernout & Hauspie Speech Products on both the recognizer itself as well as its robustness, and also the hardware implementation.
At the end, we will dip into the future and look at the continuing R&D efforts both to enhance the available algorithms, and to undertake new basic efforts in the area of application.

1. INTRODUCTION.

Amongst the most important technologies for improving man-machine-interface (MMI), voice dialogue occupies an important position. The recent progress in speech processing has led to high quality synthesizers and to reliable real-time recognizers.

The activities of a pilot in (military) helicopters are similar to those in fighter aircraft. Therefore, there exist opportunities for speech recognition and for voice synthesis in hands-busy, eyes-busy, heavy work-load situations.

However, the specific characteristics of the helicopter environment, with a more difficult acoustic noise problem, require a special kind of robustness of the recognizer. Almost all of the important special circumstances are present during a helicopter flight, with the exception of G-forces and oxygen mask noise.

Moreover, it is generally accepted that a helicopter is more difficult to fly than a winged aircraft.
These reasons explain the option to operate on a rotor aircraft rather than on a fixed wing aircraft.

2.TECHNOLOGICAL CHALLENGES.

The technological challenges that are faced in the design and development of a vocal MMI are situated on three basic levels . First, there are the basic voice processing technologies that are currently emerging and available in an office-type environment : low bit rate coding, text-to-speech and voice recognition.
Secondly, the application of these technologies into a cockpit-environment faces the researchers with the robustness of their algorithms. The performance of these algorithms is influenced by all kinds of external factors such as the Lombard-effect, the background noise, the use of oxygen mask, the pilot stress and G-forces.
And finally, there are the hardware challenges due to the trade off between the real time and the processing power requirement. Indeed the hardware has to be fitted in into a limited space, and coupled with the existing communication and avionics equipment.

2.1 Basic Technologies.

On the level of the basic voice processing technologies, one will find the speech recognizer, enabling the pilot to input commands into the system; and the audio output system, using low bit rate coding and synthetic voice for audio feedback purposes, or for warning systems.

2.1.1. Recognizing speech amounts to comparing an utterance with some references. The variability of different pronunciations by different speakers make this matching difficult due to the high variability of the input signals, in particular time warping effects.
The recognition rate typically is a function of the following parameters : the size of the active lexicon, the dependency on the speaker and the operating mode i.e. isolated words or continuous speech. But also other elements affect the performance of the algorithm, such as the preprocessing and the kind of modelling.

After a preprocessing phase, which essentially aims at the reduction of the data volume by frequency analysis, generally Hidden Markov Models or HMM (amongst the different voice recognition algorithms) are used for both isolated words and for continuous speech, possibly in combination with neural networks [1][3][9].

In essence, HMM are parametric models of the stochastic production of a vocal signal and describe voice units such as words and phonemes.
Any utterance corresponds to a path in the graph of an HMM. The statistical nature of this graph brings enough flexibility for coping with the time warping problem and simultaneously provides a probabilistic score for the decision process.
Recent improvements of the HMM are the use of durational constraints [11-13], of multi-gaussian [10] and/or semi-continuous density functions [2].
According to the nature of the probability distributions involved, a vector prequantification of the acoustic space could be required : K-means [5] and LVQ [6].

By the use of standard statistical analysis techniques (Expectation Maximization or Viterbi algorithms), one can determine the parameters of the standard models on the basis of a large number of utterances of the units. This is called training.

A speaker-dependent system is more accurate than an independent system, generally used for large public applications. There are several solutions to achieve this dependency, without adding cumbersome procedures : dynamic speaker adaptation (training) during the pre-flight check-list, or the use of a personal chip-card, on which pilot specific information is stored, such as his seat position and his voice profile.

The size of the lexicon must and can functionally be rather limited. Experience has shown that a pilot who has to "remember" too many words as commands, often has to think about the 'right' command to use, which is a waste of time in critical situations. The vocabulary can therefore be limited to 250 to 300 words. However, the real challenge lies in achieving a low perplexity of the vocabulary, that is the size of the largest subset of the lexicon that is active at any given moment during the recognition.

2.1.2. Also on the first level, one must consider the use of text-to-speech for warning messages and for audio-feedback to the recognizer. However, also prerecorded messages, using a low bit rate coding algorithm, as a voice output technique could have advantages, in particular for warning systems with short messages, although the updating of the messages will prove to be a complex matter. Text-to-speech then again will prove to be more appropriate for the generation of long variable sentences in variable situations.

2.2 Robustness.

On the second level, the PVI-system has to deal with environmental disturbances affecting in particular the recognizer.

2.2.1. The most obvious challenge lies in the problem of background noise. Note that a helicopter pilot does not wear a face mask, which would reduce acoustic noise in the microphone. In general, existing studies relate to the processing of the disturbed signal in order to find a form which is more agreeable to the listener. Classical methods are adaptive filtering and spectral substraction, while more recently methods based on neural networks and hidden Markov noise models are being studied [7].
However, the purpose of the research is not to enhance the auditive comfort, but to increase the recognition rate.
Next to that, the noise in the cockpit can exhibit some regularity (engine or propeller noise, pilot's breathing in an oxygen mask). These are no precarious signals, and one could consider original methods using correlation methods or trained noise models.

2.2.2. Also in a helicopter, there will be a drop in recognition rate due to the

mechanical vibrations affecting the pilot, changing the conditions of speech production.

2.2.3. A related disturbing factor is the so-called LOMBARD-effect [8], defined as the reflex that takes place when the speaker modifies his vocal effort while speaking in the presence of noise. With shouted speech, the vocal effort increases the energy, but decreases the intelligibility. In particular, there is distortion of consonants when speech is produced in noise. This effect has to be taken into account at the moment of the training of the system : the training has to be performed under exactly the same (noise) circumstances, or the pilot has to be trained against the LOMBARD-effect [8].

2.2.4. Speech generated under stress can cause recognition problems. Indeed, stressed speech is characterized by a sequence of non-words, stops or lack of any grammar.

2.3 Hardware.

Finally, an important challenge lies in the real time versus the processing power requirement. Indeed, the systems must be ported on a relatively small hardware platform with enough memory and processing power to assure a prompt and timely response of the system to the voice input, without reducing the performances of the existing embarked computers.

3. STATE OF THE ART.

The current research efforts have been concentrated on the following levels : the basic technologies and their robustness (3.1) and their implementation on a hardware platform (3.2).

3.1 Basic Technologies.

3.1.1. At the front level of a recognition system lays the signal preprocessing, which includes anti-aliasing filtering and sampling. The large amount of produced speech data is compressed in the frequency domain. Since speech can be considered as a stationary process on short time intervals only, a set of parameters is computed per time frame of 10ms. LPC analysis and cepstral analysis are the most widespread techniques. With both of them, the signal gets rid of the pitch, the fundamental frequency of the vocal chords which carries irrelevant information on the speaker himself, and of the prosody.
More contextual information (at the level of the acoustic representation) is retained by adding to the cepstral coefficients information about the cepstral differences between neighbouring frames. Similarly, contextual input in multilayer perceptrons (neural nets) has also led to improved phonetic classification [1].

3.1.2. The second step is the definition of models, based on a description of phonemes; a word model is then built by concatenating phonemic models, which enables us to add new words to the lexicon simply by providing their phonemic transcriptions.
An efficient description of the lexicon has been achieved by creating a

lexical tree. Here, each word is described by a path starting at the root and ending in a node or a leaf of the tree. In that way, words sharing a similar initial sequence of phonemes will have this path in common in the tree. This leads to memory space savings and faster recognition.
By an efficient use of subsets of the vocabulary the perplexity of the system has been minimized.

3.1.3. The best results of the R&D have been in the area of wordspotting. Single word recognition amounts to spotting the word out of background noise represented by garbage word models. Techniques derived from continuous speech recognition thus proven to be useful for very robust isolated word recognition (e.g. the algorithm will discard the non-words that are typical in stress conditions).

3.2 Hardware.

All the above described functional characteristics have to operate in real time. To this end, the algorithms developed in C-language on SparcStations have been implemented from the signal acquisition upto the decision process on a development DSP board (LSI TMS320 C30). The host, a PC-AT suffers no overload due to the recognition process since all computations are performed on the board. Floating point operations are far to be compulsory for recognition. except for the frequency analysis which becomes time consuming when rescaling steps are required. However, the availability of an efficient debugging tool influenced our choice of the board. Indeed, real time processing requires careful optimization of the assembler code.

Other policies can be considered where the different tasks can be shared between the board(s) and the host. For instance, integration of voice command in an electronic copilot system could take place amongst many other pilot aids and be implemented on a dedicated host while some functions only (such as anti-aliasing filtering, sampling, distance computations, ...) will be executed on the DSP board.

4. FUTURE R&D.

Two main problems are still very challenging for embarked voice command systems.

First, the recognition score should be extremely high for meeting pilot requirements. This implies a deep study of all factors able to improve robustness : more sophisticated models without impairing real time processing, lexicon pre-processing, (choice of low confusable vocabulary by using a confusion table built by the recognizer itself, creation of multiple phonetic transcriptions without using expert knowledge, ...), use of HMM/neural nets hybrid approach, determination of robust speech features, word-spotting techniques, introduction of spoken language based syntatico-semantic constraints, real time coupling with existing signal enhancement

techniques (e.g. microphone arrays, ...).

Secondly, the system should perfectly match the application requirements. This can be achieved by carefully tailoring the dialogue issues and using this information for controling recognition. Moreover, fast training, description of the lexicon in subsets, introduction of new words, speaker adaptation, background noise adaptation and acquisition channel adaptation should be implemented as a toolkit.

5. CONCLUSION.

The use of voice technology as an alternative MMI opens extremely interesting perspectives and will enable the pilot to interact with his aircraft in a more efficient way.
However, it is clear that we have still a long way to go, and that substantial research remains to be undertaken. Promising is that the basic technologies are becoming available and that the researchers have a clear view of the direction future research should take.
And who knows, we may fly our helicopter with our voice sooner than we expect !

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Discussion

QUESTION C. GULLI

For the same application, what are the possibilities for dependent and independent systems working at the same time? What are the specific fields of each?

REPLY

If the question refers to speaker independent systems, the answer is that the ultimate requirement will be that speaker independent recognisers should be used although acceptable results can currently only be obtained with speaker dependent ones. We have developed a technique called SPEAKER ADAPTATION which, within a few minutes, adapts the recognizer to the speaker's characteristics, i.e. makes it speaker dependent.

If the question refers to multiple speakers, speaking at the same time, and injecting this mixed signal into the recognizer, then the answer is that current algorithms cannot cope with this scenario!

SYSTEME DE DIALOGUE MULTIMODAL POUR COCKPITS FUTURS

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SOMMAIRE

Les dispositifs de visualisation du futur feront appel à des systèmes multimédia permettant un dialogue multimodal entre l'homme et le système.

Nous décrivons ici le concept de grand écran interactif, bâti autour d'un mur d'image en planche de bord et d'un ensemble de moyens de dialogues utilisés simultanément. Il permettra de réduire la charge de travail du pilote par une optimisation du dialogue avec le système en utilisant, entre autres, un dispositif intelligent d'aide au dialogue.

De nombreuses études ont été effectuées sur l'usage isolé de dispositifs d'entrée-sortie (clavier, souris, manche, reconnaissance vocale...) (1), mais aucune ne fait une approche globale du dialogue multimodal dans le cockpit. Nous avons donc développé et mis en oeuvre un dispositif expérimental pour étudier les interactions homme-système utilisant, l'oeil, la main et la voix.

INTRODUCTION

Les performances du couple avion-pilote tiennent pour une bonne part à la qualité du contrôle que le pilote a sur le système: le pilote, tout en recevant l'état courant du système élabore une commande à laquelle le système réagit.
La multiplicité des canaux moteurs et des canaux sensoriels humains autorise leur utilisation simultanée selon diverses combinaisons; cet avantage est actuellement peu exploité.

Le système d'interface que nous décrivons ici est bâti autour de plusieurs dispositifs d'entrée-sortie exploitant ces différents canaux; il permet l'enchaînement d'un dialogue suivant diverses modalités. Ce dialogue est supervisé par un système de gestion intelligent.

EVOLUTION DU COCKPIT

Jusqu'à ces dernières années, l'interaction homme-machine s'effectuait à l'aide de dispositifs simples à modalité unique (affichage sur cadran, manche, bouton de commande). Les limites de cette structure de cockpit ont rapidement été atteintes au fur et à mesure que la complexité et la diversité des tâches demandées à l'avion de combat se sont accrues.
Désormais, le pilote dialogue avec un système en échangeant des données, c'est-à-dire, des entités abstraites. Il sera aidé dans sa mission par un copilote électronique (2).
La communication, quant à elle, a besoin d'une interface adaptée, telle qu'un grand écran interactif; celui-ci permet l'établissement d'un dialogue multimodal qui se rapproche, par là-même, de la communication naturelle.
Les expérimentations préliminaires (3,4) que nous avons déjà menées sur cette interface ont montré qu'une analyse des interactions homme-système est indispensable pour créer une interface optimum de dialogue multimodal.

ARCHITECTURE MATERIELLE

Donnée en figure 1, elle est constituée des trois sous-ensembles suivants: les médias d'entrée ou de sortie, le processeur de gestion, la source d'images.

Médias de sortie

- Un rétroprojecteur LCD fournit des images couleur de 440 x 480 pixels sur un grand écran de 520 x 400 mm2 occupant toute la planche de bord.
- Un synthétiseur vocal (Datavox).

Médias d'entrée

- Un oculomètre (NAC EMR-V) mesure la direction du regard par rapport à la tête à l'aide d'une micro-caméra analysant le reflet cornéen d'une diode infra-rouge éclairant l'oeil droit.
- Un système de reconnaissance de la parole en continu (Datavox), déclenché par détection d'activité, effectue une analyse phonétique et syntaxique du signal après l'avoir séparé en messages et en mots.
- Un dispositif à fibres optiques, équipant un gant porté par la main, permet de mesurer l'angle de flexion des deux premières articulations de chaque doigt (Data Glove de VPL Research).
- Des capteurs électromagnétiques (Polhemus 3 Space Isotrak) couplés à des émetteurs fixes donnent position et orientation de la main et de la tête.

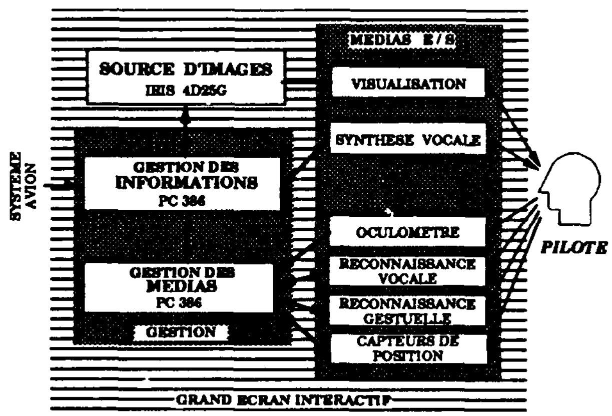

Figure 1: Interface pour dialogue multimodal.

Processeurs de gestion

- La gestion des médias est assurée par un PC 386/20 MHz; il canalise les données brutes fournies séparément par chaque média, et délivre un message multimédia au processeur de gestion du dialogue.
- La gestion intelligente du dialogue est effectuée par un autre PC 386/25 MHz; celui-ci commande la source d'images et le synthétiseur vocal.

Source d'images
La station de travail IRIS 4D25G fournit, au rétroprojecteur, les images de type TV (figure 2). Renouvelées à un rythme dépendant de leur complexité (environ 8 Hz), elles sont constituées pour l'essentiel:
- en zone centrale, de fenêtres variables en taille et en position, chacune contient une figuration avionique de type déterminé, elles peuvent se superposer partiellement ou totalement suivant plusieurs plans.
- en partie inférieure, d'étiquettes représentant l'état des fenêtres (présence à l'écran) et celui des médias (marche, arrêt, panne), ainsi qu'une zone de sécurité présentant les fenêtres prioritaires, en médaillon.

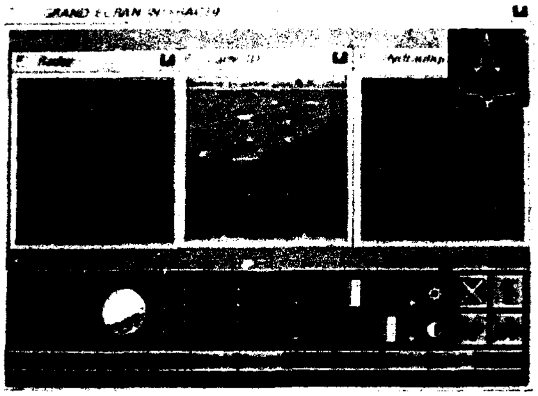

Figure 2: Image interactive présentée par le grand écran constituant la planche de bord.

LES ELEMENTS DU DIALOGUE

Regard
Sa direction, calculée en permanence à partir de l'orientation de l'oeil et de la tête, est indiquée par un symbole spécifique, mobile sur l'écran; l'activité de la main a priorité sur ce canal.

Voix
Le vocabulaire est volontairement restreint à 36 mots, regroupés en messages de 1 à 3 mots.

Main
Les 4 postures signifiantes sont:
- "*désigne*": index tendu, autres doigts repliés.
- "*o.k.*": pouce levé.
- "*pris*": main fermée, doigts tendus.
- "*stop*": main ouverte, pouce replié.
Le suivi de désignation de l'index est assuré par un symbole spécifique mobile sur l'écran

Les 5 gestes signifiants sont:
- "*prendre*": main proche de l'écran, puis se refermant en posture "pris".
- "*lâcher*": quitter la posture "pris".
- "*jeter*": lâcher après s'être éloigné de l'écran.
- "*rotation droite*": tourner la main de 30° sur elle-même, en posture "pris".
- "*rotation gauche*": tourner la main dans le sens inverse.
Dès que la main est suffisamment proche de l'écran, un symbole spécifique, donne sa position courante.

FINALITES DU DIALOGUE

Les actions commandées par l'opérateur sont actuellement simples et en nombre réduit; elles portent,
- soit sur l'espace graphique lui-même, par modifications des fenêtres: présentation à l'écran, disparition, déplacement, changement de taille, mise au premier plan,
- soit sur les médias: mise en marche, arrêt.

EXEMPLE DE DIALOGUE MULTIMODAL

Pour commander la disparition d'une fenêtre déjà présente à l'écran, l'opérateur dispose de 5 modalités différentes de dialogue avec le système (A: action opérateur; R: réaction système); la fenêtre contient, par exemple, une figuration radar.

1) Verbalisation totale:
A= voix: "fermer - radar".
R= disparition de la fenêtre radar de l'écran.

2) Verbalisation et désignation manuelle :
A= posture de main: "désigne".
R= apparition du symbole de désignation.

A= mouvement de la main.
R= suivi du mouvement par le symbole.

A= index désigne la fenêtre radar + voix: "fermer".
R= disparition de la fenêtre radar.

3) Verbalisation et désignation au regard:
A= mouvement de la direction du regard.
R = suivi du mouvement par le symbole du regard.

A= regard sur la fenêtre radar + voix: "fermer".
R= disparition de la fenêtre radar.

4) Manipulation de l'objet graphique:
A= main proche de l'écran.
R= apparition du symbole de main.

A= mouvement de la main devant l'écran.
R= suivi du mouvement par le symbole.

A= main face à la fenêtre radar + geste "prendre".
R= apparition d'une fenêtre-squelette sur la fenêtre radar.

A= mouvement de la main en préhension devant l'écran.
R= suivi du mouvement par le squelette et par le symbole de main.

A= éloignement de la main en préhension.
R= disparition du squelette et du symbole de main.

A= geste "lâcher".
R= disparition de la fenêtre radar.

5) Manipulation d'une métaphore de l'objet graphique:
A= main proche de l'écran.
R= apparition du symbole de main.

A= mouvement de la main devant l'écran.
R= suivi du mouvement par le symbole.

A= geste "prendre" sur l'étiquette représentant la fenêtre radar.

R= apparition d'un symbole circulaire en superposition de l'étiquette.

A= geste "rotation gauche".
R= changement de la couleur de l'étiquette et disparition de la fenêtre radar.

A= geste "lâche".
R= disparition du symbole circulaire sur l'étiquette.

LOGICIEL DE GESTION DU DIALOGUE

Le système expert, écrit pour l'essentiel en langage Prolog de façon à faciliter son évolution en phase de mise au point, constitue le coeur du traitement; il contient:
- un module de compréhension par analyse syntaxico-sémantique simple du message multimédia issu du serveur multimédia,
- les règles de gestion de l'application qui déterminent la validité du message et les conséquences qu'il induit sur l'espace graphique,
- les règles de sécurité,
- la base de faits statiques qui comprend les lexiques vocal et gestuel, la position par défaut des fenêtres, les fenêtres prioritaires...,
- la base de faits dynamiques précisant, par exemple, l'état de chaque fenêtre (position, taille, présence à l'écran), la disponibilité des médias, l'objet désigné, la position initiale, la taille et le type de l'objet manipulé, la proximité de la main par rapport à l'écran ...

PERFORMANCE ET MULTIMODALITE

Des expérimentations préliminaires ont porté sur la capacité d'utilisation bimodale de ces nouveaux médias. D'autres expérimentations, en cours, portent sur la mesure des performances d' un dialogue multimodal.

CONCLUSION

L'efficacité du contrôle et de la supervision d'un système complexe, tel que celui des avions de combat modernes est fortement dépendant de la structure de l'interface homme-machine; la souplesse que lui confère le caractère multimodal de celle que nous avons construite permet d' adapter, en temps réel, le mode d'échange.
Une optimisation de l'efficacité du dialogue est ainsi rendue possible.

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Principles for integrating voice I/O in a complex interface

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SUMMARY

The integration of voice into a complex interface like that between a pilot and an aircraft is not trivial. In this paper, we try to address some of the factors affecting the use and integration of voice in human-machine interfaces. We describe general principles for merging different kinds of human-machine interaction, and apply them to voice interaction in the cockpit. We do this despite published opinion that psychological principles cannot be applied in the design of human-computer interaction (e.g., Landauer, 1991).

The theory of Layered Protocols (LP) is introduced in context of the more general Perceptual Control Theory of behaviour (PCT). LP theory provides a model for describing interaction between complex partners based on a layered structure of protocols that differ in levels of abstraction. The proper use of feedback is fundamental to both LP and PCT.

Voice interaction is useful mainly for the control of tasks requiring discrete information. Failure of voice recognition systems is often caused by inappropriate feedback. Providing feedback and forcing correction word by word may increase the mental load on a user, often leading to instability in the interaction. Such inefficient, and often frustrating, use of voice interaction can often be overcome through the use of feedback at higher, more abstract, layers of interaction. Successful adoption of voice interaction depends on allocating the appropriate tasks of communication to the voice protocol, the dynamic modeling of the partner, and the use of higher level protocols to help control potential instability.

INTRODUCTION

Many people think that the problem of getting our machines to do what we want would be greatly eased if we could talk to them. Experimental aircraft such as a BAC-111 airliner in the UK and the Mirage IIIB fighter in France have been provided with voice I/O for this reason. But not all attempts to use voice have been as effective as their proponents hoped.

The blame for failure of voice I/O is often placed on the error rates of word recognition, but other factors may actually be more important. For example, in an effort to allow the talker to correct recognition errors, the designer may place a visual display of the recognized speech somewhere the talker can see it. But if there are only a few errors the talker may well miss them on the display. In addition, the display may both distract the talker from other visual tasks and take up valuable space in the cockpit. Such a visual read-back of the words recognized may be more harmful than helpful to the use of voice in the cockpit. But under some circumstances, it could be exactly what is needed.

A general approach to communication

The theory on which we base our analysis is known as the Theory of Layered Protocols (LP; Taylor, 1987, 1988a, 1988b, 1989). LP is a general theory of communication, compatible with an approach to psychology known as Perceptual Control Theory (PCT; Powers, 1973), and is readily described in its terms. PCT is well suited to the description and analysis of interactions with inanimate objects, whereas LP emphasizes the mutuality of interaction between "intelligent" partners, and can be seen as a specialized form of PCT.

The theory of Layered Protocols (LP) is based on a long tradition in psychology that people perceive, remember, and act at a number of levels of abstraction, the lower levels supporting the higher. LP theory, like PCT, is based on the properties of a hierarchy of control systems, but focuses on control loops that incorporate a partner with some independence of perception and of action.

LP theory is the focus of this paper, but before discussing it in any depth, we present a brief introduction to PCT, to help lay the groundwork.

Perceptual control theory

According to PCT, all behavior is directed to the control of perceptions at a variety of levels of abstraction simultaneously. A perception might be the tension in a muscle involved in the turning of a steering wheel that allows a driver to perceive the car as staying on the road during a trip for money for the purchase of food that allows the driver's body chemistry to stay within survivable bounds.

In the PCT view, all living things consist of a hierarchy of control systems that maintain their percepts at desired levels by means of actions they perform on the outer world. In very simple organisms such as bacteria, there may be only one level in the hierarchy, and only one possible action (e.g. "wiggle"), but this suffices to move the bacterium from noxious environments into suitable ones more often than not. In more complex organisms, there are more levels of control. Actions are, like the perceptions they control, organized at different levels of abstraction. The driver is "doing" many different things at once: following a life plan, performing a job, getting wages, driving, following a bend in the road, turning the steering wheel, and tensing certain muscles, among other behaviors (Vallacher & Wegner, 1987). A feedback loop controls each perception of the situation, as shown in Figure 1.

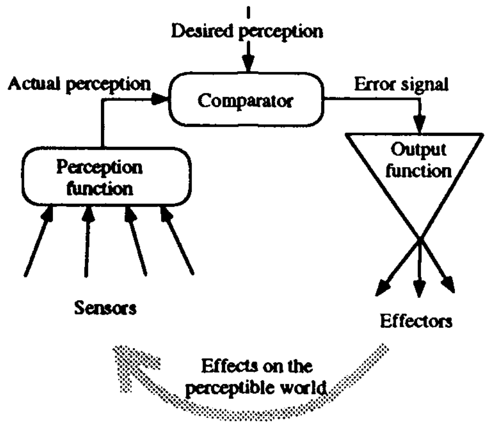

Figure 1. An elementary control system compares its perceptual input with a desired (reference) percept, and outputs the difference as an error signal that causes effects to happen in the world. These effects modify the perceptual signal in the direction of the desired percept.

An elementary control system (ECS), such as shown in Figure 1, is a unit of a control hierarchy. An ECS has a percept that is derived by some function from the sensory input from a variety of sources, including lower-level ECSs; it has a reference signal derived from a multiplicity of signals from higher-level ECSs, and it has a error signal that is the difference between its reference and its percept. Some amplifying operation converts the error signal into a set of reference signals for lower order ECSs, or, at the lowest level, into action signals for effectors (muscles), as shown in Figure 2. The amplified error signal, usually caused by unpredicted events in the environment, leads to behavior that alters the perceived state in, the protagonist hopes, the desired direction.

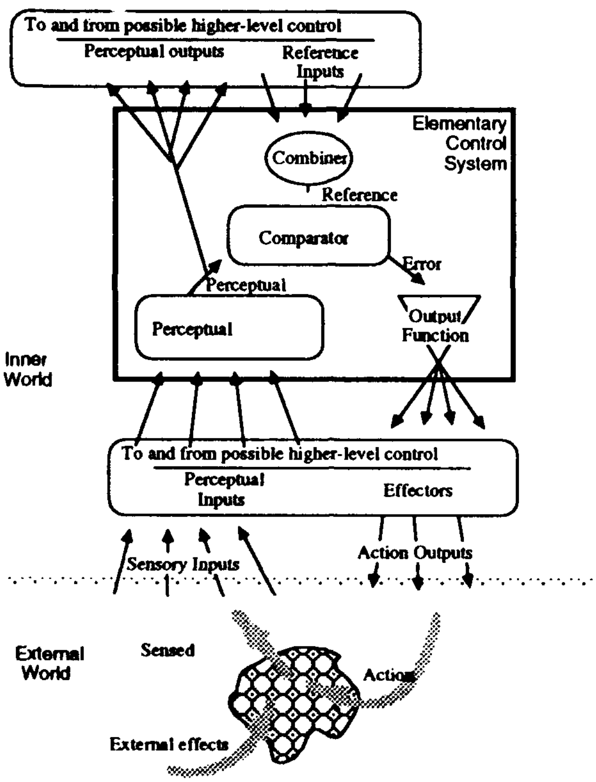

Figure 2. An Elementary Control System is normally connected to other control systems at both higher and lower levels, permitting the control of arbitrarily complex percepts.

ECSs are connected in a hierarchy in which the perceptual signals of low-level control systems combine to provide the sensory inputs to higher level ones. The connections among the perceptual elements in the hierarchy could be seen as a multi-layer neural network. Such a hierarchy could develop perceptual functions of arbitrary complexity (e.g., Lippmann, 1987).

In the same way that the perceptual function of a lower-level ECS provides one of the inputs to the perceptual funtion of a higher one, so do the action outputs of high level ECSs combine to provide the reference signals for low-level ECSs. Figure 3 shows a sketch of such a hierarchy, in which the lowest ECSs affect and sense the world of perceptible things directly. These "perceptible things" include the aircraft being flown, as well as communicative partners.

In a "classical" PCT hierarchy, the signals (percept, reference, and error) are all scalar. If, however, one looks at a set of ECSs at the same hierarchic level acting in parallel, the effect is almost the same as if there were one ECS with a vector percept, reference, and error. More complex structures for the signals can also be considered, so that we can talk about the control of perceptions of arbitrary complexity.

In the hierarchic control system depicted in Figure 3, each of the control systems at any level of the hierarchy attempts to

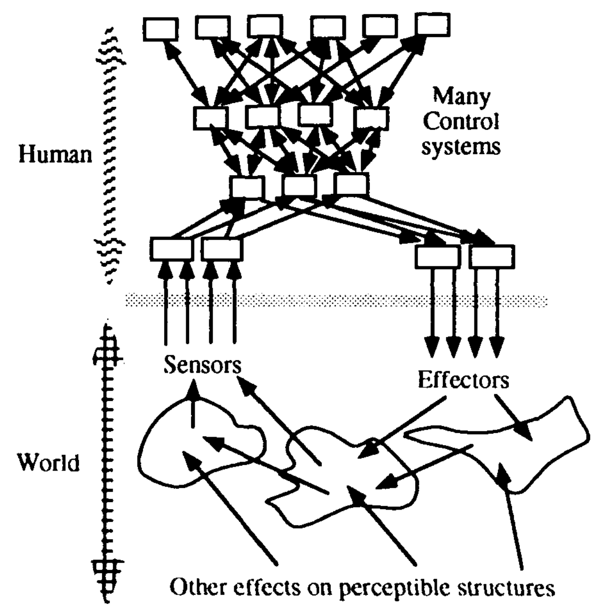

Figure 3. A generic view of hierarchic perceptual control structures by which the human uses behavior to control perceptions. Higher level control systems receive perceptual inputs based on lower-level perceptual patterns, and provide outputs corresponding to the differences between what they perceive and their reference percepts. These outputs represent references, or goals, for lower level control systems, the lowest of which control the effectors that act on the world, changing the percepts experienced by all the control systems.

act so that its percept agrees with its reference percept. The higher level control systems do this by adjusting the reference signals sent to lower level systems. The lower level control systems have very concrete percepts (and references, therefore) that depend directly on the signals impinging on the sensor organs. At higher levels, the percepts represent more abstract structures, not directly observable by the sense organs.

One can see a structured control system as a goal-seeking device. It works toward ever changing goals defined by its structured reference signals. For example, the reference percept for a pilot may be the perception of a safe landing at the destination airport. The achievement of that goal involves setting several other reference percepts for lower-level ECSs, such as the perception of passing a given sequence of waypoints, the perception of flying at a particular altitude, and so forth.

Communication

In the framework of either Perceptual Control Theory or Layered Protocol theory there is no structural difference between controlling an inanimate tool and communicating with an intelligent partner. A communicative partner is part of the perceptible outer world that is affected by behavior. But unlike a tool, an "intelligent" communicative partner has its, his, or her own control systems that perceive and act. We give the name "virtual messages" to communications between the high-level structures of the protagonist and corresponding ones of the partner.

We take communication to cover a wide range of interaction, from simple use of a tool at one pole of a continuum, to complex discussions such as philosophical argument at the other. We describe both sorts of interaction in the same way, using the same principles, but with great differences in the quantitative aspects of the interaction structure.

Whether the partner is a machine or a person, the protagonist performs some action that affects the partner's behavior in some detectable manner, as shown in Figure 4. A pilot may pull back on the stick, and the partner (the plane) begins to climb; or a philosopher may present an argument to which the partner responds with a counter-argument. In either case, the fundamental construct is a feedback loop. If the climb is too steep or not steep enough, the pilot changes the angle of the stick; the philosopher changes some part of the argument, augmenting, explaining, correcting in a way calculated to bring the partner to agreement. In either case, the protagonist behaves in such a way as to perceive a desired situation.

Using a different terminology, the protagonist has a perceptual goal that may be achieved through behavior. The success of the behavior in bringing the goal closer is monitored, and the behavior altered accordingly. If the achievement of the goal involves communicating with a partner, there is a communicative goal, which may be achieved through either dialogue or non-dialogue methods, depending on the protagonist's model of the partner and on other circumstances, such as whether the protagonist wants the partner to realize that the communication is happening, or whether the partner is even capable of engaging in dialogue.

There is a critical difference between using a tool and communicating with an intelligent partner. The tool has no goals of its own—no reference states that it uses to set desired percepts that might conflict with those desired by the protagonist. The tool is neither cooperative nor antagonistic, whereas a human communicative partner may be either, but is unlikely to be passively neutral in respect of the communication. The tool is reactive, whereas the person may be proactive. An "intelligent" machine falls somewhere between, in that it can be controlling sensory inputs to accord with references that are set independently of, and may be unknown to, the human user. A computer-controlled aircraft that has flight envelope limits built into its program may "deliberately" thwart the intentions of a pilot to perform some manoeuvre. Such a machine is the kind of partner that we consider in this paper.

Background to Layered Protocol theory

The principles we will be describing are part of the Layered Protocols (LP) theory of communication between "intelligent" entities. In this context, "intelligent" implies not cleverness so much as a degree of independence between the entities in three respects:

- independence of design,
- independence of sensing mechanism, and
- independence of action.

Independence of design means that neither partner can be sure precisely how the other will interpret any specific communication. Independence of sensing mechanism means that neither partner can know exactly what information the other has available. Independence of action means that neither partner can know at any moment all of what the other is doing. Independence of action lies at the heart of the link

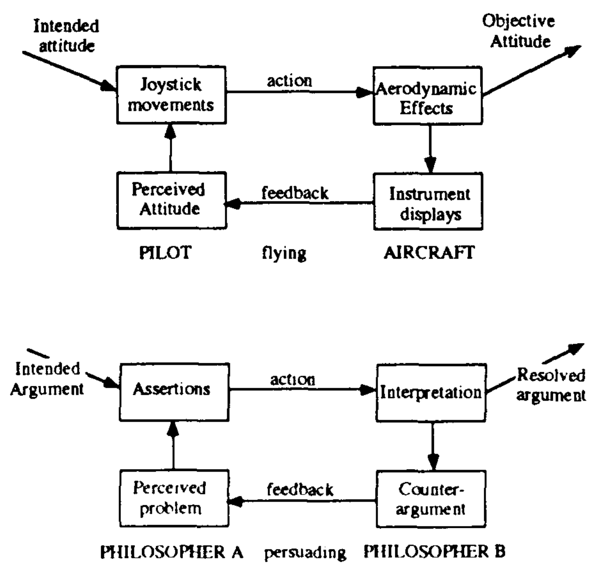

Figure 4. The formal similarity between controlling the attitude of an aircraft and communicating a persuasive argument. In either case, the important issue is whether the protagonist (on the left, in each part of the figure) can come to perceive that the effect on the partner is as desired.

between "intelligence" and independence, because it is the ability of an entity to perform actions that bear a useful relation to its circumstances that normally leads one to classify it as "intelligent."

Communications between a pilot and an aircraft largely fulfil the three independence criteria, and will increasingly do so as computerization of aircraft proceeds. The aircraft and the pilot clearly were not designed together; the aircraft has many sensing systems not directly accessible to the pilot, and vice-versa; and the aircraft can perform actions, such as manipulating information, that are not known in detail to the pilot. As a trivial example, when the aircraft is on autopilot, the pilot may not even be aware of some of the flight events it performs.

The independence criteria mean that neither communicating partner can be aware of the exact effect of any particular communication. Under these circumstances no message can be encoded with sufficient redundancy to guarantee error-free reception, in contrast to the classical situation in which the only communicative difficulty is noise in the communication channel and reception delay associated with error-correction coding. With independence, the receiving partner must provide the transmitter with feedback that helps each partner to believe that the intended message was the one received, and to correct the situation if it was not.

When feedback enters the situation, questions of stability arise. If the feedback is delayed, has too strong an influence on the forward channel, or changes too rapidly, the whole connection may be dominated by instability in the feedback loop, to the exclusion of the information that is supposed to be transmitted. The stability criteria for feedback systems would oppose those for rapid and effective information transmission, if a single error-correcting feedback loop were used (Taylor, 1989). But the effects of the opposition can be reduced by dividing the work among a hierarchy of feedback systems, each of which occur over successively longer time scales. In voice, for example, corrections can be made at the level of word ("what word was that?'), proposition ("You mean alter the map display?"), or higher-level constructs ("You mean to suggest that we will have very little fuel reserve?").

Before considering the Layered Protocol theory in more detail, let us discuss some considerations relating to the voice channel through which much human-human (and very little human-machine) communication is passed.

Voice in aircraft

What kind of material is suited for voice input? In human communication, voice is used to communicate subtle relationships among a wide range of concepts, a range much wider than can be accommodated by gesture or by any other means of communication, except possible gestural language such as American Sign Language. Only writing offers a comparable range of possibilities for communication, and it is restricted by its inability to convey nuances of affect.

In communicating with a machine, voice cannot be used in its "natural" function, for two reasons. Firstly, current and projected recognizers have neither the range of vocabulary nor the ability to deal with intonational modulation demanded by normal conversation; secondly, the machines with which we might wish to communicate do not have the intelligence to interpret the kind of subtleties that humans are accustomed to conveying by voice. In dealing with machines, humans must use voice in an unnatural way, restricting the vocabulary and relying on words by themselves to convey the intent of the communication. Indeed, voice recognition by machine has ordinarily been taken to be a problem in word recognition, and only occasionally until recently has there been any significant interest in speech understanding (e.g. Klatt, 1977). Why, then, should anyone want to use voice in interacting with machines?

Flying an aircraft is fundamentally a question of making it go where the pilot wants it to go, and perhaps to perform other manoeuvres while it is doing so. From moment to moment, going where the pilot wants is a problem in continuous control, but on a longer time scale the problem is discrete—the plane should arrive at this airport or that, maintain this altitude or that, pass through this waypoint or that. Voice is adequate for communicating discrete information, but not for continuous control. It follows, then, that the tasks for which voice should be used are not those in which the pilot needs continuous control. It also follows that the tasks that use voice must be integrated with those under continuous pilot control, and in an "intelligent" future aircraft with tasks controlled by largely autonomous subsystems.

Voice is not the only means by which the pilot can communicate discrete symbolic information to the aircraft. Voice must compete with pushbuttons, keyboards both soft and hard, and even possibly with voice communication to other humans. If there are few choices and very clean error-free communication is required, a pushbutton may be more appropriate than voice, provided that the pilot has a hand free to push it, and perhaps eyes free to see it pushed correctly.

One may not want to use voice when the timing of an event is crucial. Fingers are much better than voice for exactly timed events. It may be appropriate to arm a weapon by voice, but not to activate it. An error in arming can be retracted, but a gun cannot be unshot, or a bomb undropped. A weapon used at a time 200 msec from optimum might as well not have been used. Even in far future aircraft with excellent voice recognition capacities, it is unlikely that spatially discrete buttons and switches will be totally superseded by voice.

What, then, is voice good for? Primarily for strategic information, communication that is not time-critical, the control of other interactions and displays, and in general those things that involve selection among many discrete possibilities that can combine in different ways and in which errors are recoverable. Voice is particularly useful when the hands and eyes are otherwise occupied, and this is the main reason for wanting voice in the cockpit at all.

Voice recognition equipment has its limitations, especially in complex, rapidly changing situations such as are encountered in an aircraft cockpit. Natural human voice communication is less syntactically constrained than is written text, but recognizers for continuous speech usually demand ad-

herence to a fairly rigid syntax as the price of recognizing an adequate vocabulary. In stressful situations, people may forget to use the correct highly constrained syntax. On the other hand, it has been reported that in emergency conditions when the pilot has a chance of landing safely, the language may revert to the correct form, perhaps because it takes less cognitive resources to use the highly trained forms than to invent new dialogue. Even in conditions of relatively low stress, such as normal air traffic control (ATC) interactions, pilots and controllers often go well beyond the bounds of the prescribed syntax, and this has presented significant problems to researchers attempting to use voice recognition as a component in training systems for ATC (F. Néel, Personal Communication, April 1990).

Speech recognizers tend to have trouble during conditions of stress, although the few existing studies of stressed voice show no consistent trends in the parameters of speech (C. Weintstein, Personal Communication, April 1992). It is probable that the stressed voice is more variable than the unstressed voice, and this causes recognition errors. But it is particularly in stressful conditions that the accuracy of the recognizer is most important.

People tend to stop talking while they deal with immediate control problems, so it is likely that voice is best used for tasks that can be postponed until immediate stresses have passed, or that involve preparation for later periods of stress. This will not necessarily be true if the use of voice is part of the trained behaviour to deal with the stress condition, but it otherwise imposes some restrictions on the machine side of the interface, because synchronization between voice and other controls may not be reliable.

Voice in the cockpit faces a hurdle not placed in the path of traditional means of communication between the pilot and his aircraft. Voice is psychologically required to be error-free, whereas keyboard entry for the same task is not. Why? Could it be that error detection and recovery is thought to be easier and quicker for keyboard entry than for voice? In fact, voice entry for numbers may well be more accurate than through a keyboard, even under office conditions in which keyboard entry is easy. Or is it that the pilot knows that the keyboard will accurately report the character corresponding to the pressed key, whether the key be right or wrong, whereas the voice recognizer will sometimes report the wrong word even when the pilot speaks the correct one? In military action, operators (pilots) must have confidence in their abilities and their equipment, whether or not either be warranted.

STRUCTURE OF A MULTIMODAL INTERFACE

To see where voice fits into a Layered Protocol structure, we must first deal with the general question of how the theory of Layered Protocols can be used to describe a complex interaction between "intelligent" partners. The principles are quite general. To apply them to specific situations, the details must be filled in, but the structure remains the same. The Layered Protocol structure we describe here is somewhat evolved from that presented by Taylor (1988a, b; 1989), but most of what was described there is still valid.

Support structure

A Layered Protocol interface has two important aspects: the protocols, and the layered support structures that link the protocols. Let us first briefly consider the support structure, before we deal in more detail with the nature of protocols. For now, assume that a protocol is a means whereby a chunk of information to be communicated is transformed into some less abstract form by the transmitting partner, and interpreted by the receiving partner, possibly after much feedback and correction, into a similarly abstract (though possibly different) form, as shown in Figure 5. The "chunk" might be the information whose transmission constitutes the original communicative goal of the transmitter, or it might be the result of a transformation performed by a higher-level protocol, as shown in Figure 6. In either case, the result of the transformation performed by the protocol is a "virtual message" that passes between the two parties. Only when the successive transformations have arrived at physical phenomena such as sound waves or photon streams can the messages be termed "real."

Virtual messages are realized by means of actions that may take different forms under different circumstances; the same message may be transmitted by voice on one occasion, by gesture on another, and on a third by a combination of the two. It does not matter which mode is used, provided that the result satisfies the protagonist's requirement to perceive that the virtual message was received. It is the beliefs or percepts of the originator, not the recipient, that determine the need for, the means of, and the success of, the communication.

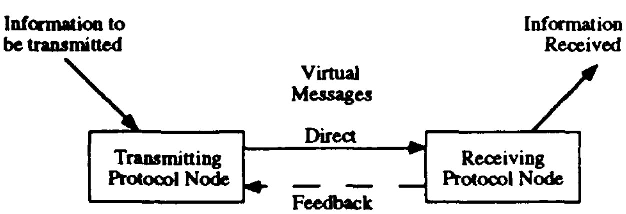

Figure 5. A Protocol converts information to be transmitted into a less abstract form that is communicated to the partner. The protocol may require feedback to ensure correct transmission, but the virtual message goes only one way, and is interpreted by the recipient at the same level of abstraction as the original information that was to be transmitted.

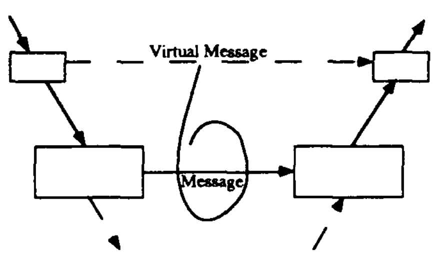

Figure 6. The information that is transmitted by a protocol may be the virtual message of a higher level protocol. The lower-level, less abstract, protocol is said to support the higher-level one. Feedback connections are important at both levels, but are not shown in this figure.

Those beliefs are most strongly affected by feedback from the recipient, and it is the highest level of feedback that matters most. If high-level control systems are satisfied, lower-level ones need not do anything. But higher-level systems are more likely to be satisfied if lower-level ones perform properly.

Sometimes information is more easily transmitted in one form, say verbal, and sometimes in another, say pictorial. Or perhaps part of a higher-level message may be transformed into words, and another part into pictures, as happens, for example, with labels on a map. In this situation, two protocols support the transmission of a single chunk of information, as in Figure 7. Such an arrangement is known as "diviplexing." The converse, multiplexing, also is common; one lower protocol supports two higher ones simultaneously. Multiple windows on a computer screen provide a well-known example. The screen is a single visual display channel, but different processes communicate with the user through it, distinguishing their outputs by locating them within different windows on the screen surface.

The whole structure of support within the network is an acyclic graph, in which converging and diverging threads of support allow multiple kinds of high-level messages to be communicated through a variety of physical media. Virtual messages are transformed and transformed again, into ever less abstract forms, before being physically transmitted to the partner, where they are reassembled and interpreted.

An important issue is how the partner can determine the interrelations of the partial messages being transmitted by the various different means. What signals how two diviplexed messages ought to be recombined, or in a multiplexed message how the components with different destinations should be identified? The necessary information must be in one of two places: *in the message forms, or in specific prior knowledge of the receiving partner*. If it is in the message form, then it is part of the protocol for that type of message, as, for example, in the protocol that whatever appears within the frame of one window on the screen must belong to a single task.

Protocol Structure

A protocol has a simple job: to take as a goal the transfer of some chunk of information from one partner to the other by

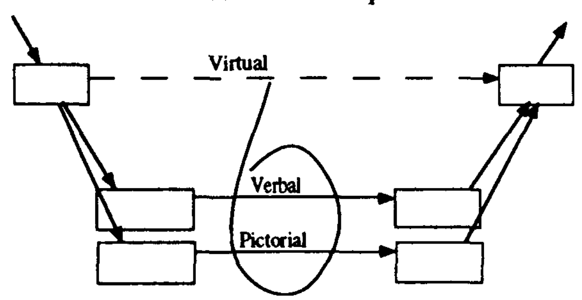

Figure 7. It is possible for a higher-level protocol to be supported by more than one lower-level protocol. This arrangement is called "diviplexing." At the higher level, information may be transmitted in the form of a map, for example, which at a lower level is transmitted partly in pictorial and partly in verbal form. Feedback connections are omitted for clarity in this figure.

transforming it into some less abstract form that the protocol is able to transmit. The protocol is executed by a pair of "protocol nodes," a transmitting node in the originating partner, and a receiving node in the recipient partner. The protocol may, but need not, take advantage of situation-specific information such as information about the partner, the task, the local state of the world, the recent and planned dialogue, and so forth. In its simplest form, the protocol may simply translate the originator's intent to pass a character, say, into the depression of a key on a keyboard, which is directly interpreted by the recipient (computer) as the transmission of the character. Similar simplicity would attend the transmission of a spoken word through a very reliable recognizer that gave no feedback (if such a thing were to exist); the user would speak the word (translating it into a pattern of acoustic waves), and the recognizer would reconvert it into a computer representation of the same word with no further ado.

Such error-free transmission is rare, and perhaps impossible even between partners that lack the three independences (Elias, 1953). People do mistype, hitting the wrong key even though they know which one they intend to strike; speech recognizers do make errors, even though the user speaks the correct word clearly. In either case, if the errors are not detected and corrected, higher-level protocols must be designed to accept the erroneous keystroke or word, and to perform acceptably in spite of the error. The options, then, are to correct errors before they are taken as truth by higher-level protocols, or to accept that errors will be made, and to ensure that the higher-level protocols are flexible enough to handle them.

People do not normally speak with the expectation that their partner will query each dubious word. They expect that the partner will try to make sense of what they are saying, despite the fact that many words are slurred, shortened, or even omitted. Think of the typical American pronunciation of the word "President," as in "Pres'n Bush." The word "and" usually is pronounced as "n" if it is not acoustically omitted entirely. Such "flaws" at the word level cause no difficulty to a fluent English speaker listening to them, though they may well make it impossible for a less fluent listener to understand the speech at all. The internal redundancies in the structure of the sentences allow the missing or deficient words to be reconstituted with almost total accuracy. Listeners rarely are even aware that the reconstruction has occurred, unless they listen very critically. Word-by-word feedback of what the recognizer has recognized is therefore not likely to be part of a good set of protocols for dealing with voice input, unless the recognizer performance is very poor.

A second conclusion about these simple protocols without feedback, implicit in the foregoing discussion, is that the results are almost never used directly, but are part of a larger message. It is true that in a simple tool-using protocol the push of a button is the signal for something to happen, often independently of any prior tool manipulation, but even there, the effective action is often part of a larger sequence. Feedback can be omitted if and only if (a) the message is with high probability going to be properly interpreted, and (b) the message will be incorporated into a higher-level message

that does have feedback, or will be used in an observable and correctable way to affect the outer world.

What is the point of feedback? To understand this, we must go further into the whole process of action and communication.

Feedback

A protocol node has functions quite analogous to those of an ECS, as shown in Figure 8. The protocol node in the originator has a goal that the recipient's receiving node should have some chunk of information, and a reference belief about what information the partner has; it performs an action in the form of a virtual message intended to affect the partner's belief in the desired direction, and acquires feedback that allows it to modify its beliefs and perhaps alter the way it presents the virtual message. Parallel relationbships hold for the receiving node.

The key to the action of the transmitting protocol node is in the relation between the Model on the one hand and the Coder and Decoder on the other. The Model is the analogue to the comparator of the ECS. It compares the chunk of information to be sent with that believed to be known to the recipient. How complex is the comparison that leads to the output message? At very low levels, the Model is vestigial, and the Coder and Decoder do all the work. By design, a low level protocol node always assumes that the partner does not have the information, so the virtual message carries it. For example, if a keyboard command requires the letter "p," the user presses the "p" key. All of the behavior of such a low-level protocol node is determined by the Coder (or, in a receiving node, by the Decoder).

In contrast, at very high levels, almost all the work is done in the Model, and the Coder and Decoder are relatively simple. At these levels, the partner probably already knows much of the information that the originator wishes to get across, or at least has analogous information that can be used to assist in the encoding process.

The question of what the partner knows or ought to know is crucial in determining the need for feedback. From the viewpoint of the recipient, if the originator probably believes that the message has been successfully received, there is no need to provide feedback. On the other hand, if the recipient believes that originator quite probably is uncertain what message was received, then informative feedback is required. As Pask (e.g. Pask, 1980) points out, informative feedback should normally not be a mere echo of the overt content of the message. Rather, it should be some reinterpretation of the message in a different form that the originator can recognize as having the same intention.

For voice, the worst feedback probably is a vocal echo, which is subject to a set of error probabilities very like those that applied to the original vocal message, so that the speaker may well misinterpret the echo of a wrong recognition as being correct. What kind of feedback is best for voice will depend on the situation and the probability of error in the voice recognition equipment. It might even be a vocal paraphrase of the spoken material, but is more likely to be an entirely different kind of presentation.

As an example of appropriate feedback, consider the use of voice to control a map display of variable scale that shows the region centred on the aircraft, such as in the experimental BAC-111 flown by RAE Bedford. In this aircraft, the pilot can issue a command something like "Map range fifty miles" to set the range of the outer ring of the map. The experimental recognition system incorporates a visual display that shows the words recognized, but this display is ordinarily used only by pilots for whom recognition performance is bad (Moderator's comment in Taylor, 1987). A pilot for whom recognition is normally good discovers whether a particular recognition was correct through the action of the map display, which may change to the wrong range, if, for example, "fifty" is mistaken for "fifteen." In such a case, the pilot merely corrects the effect of the message by using a new command, perhaps repeating the original. The error would not be repeated if the system were designed to make the pragmatic assumption that a "map range" command is intended to change the range.

The primary reason for introducing voice into the cockpit is supposed to be to reduce the load on the pilot's resources, not to give him more capability. After all, there is very little that voice can do that cannot be done tactually. However, keying a number can distract the pilot from flying the aircraft more than does saying the number. In low-level flight, it is important that the pilot fly accurately, and voice is therefore a desirable means of entering numbers, provided the numbers are usually recognized correctly. But if the pilot is not assured that the number will be assigned to the proper function, the use of voice to enter it will not be very helpful.

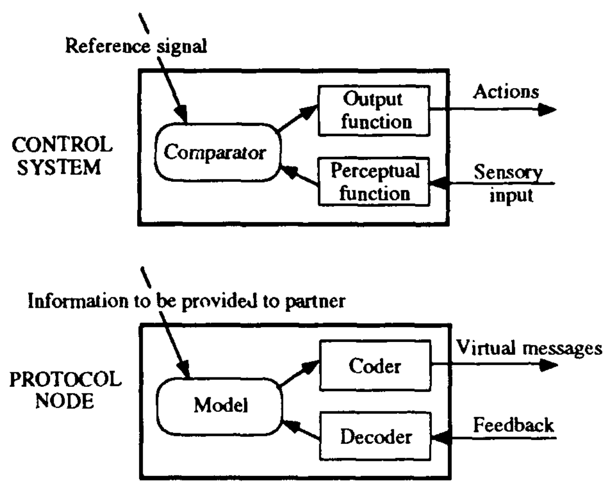

Figure 8. Analogy between an elementary control system and a protocol node. In the control system, incoming perceptual data are evaluated and compared with some reference that represents the desired percept. The difference between the two results in some virtual actions that are actually performed by lower-level control systems. In the protocol node, the information that the partner should have is compared with a model of what the partner does have, the difference resulting in a virtual message implemented by lower supporting protocols. The model is affected by the resulting feedback, which may result in further virtual messages.

An error in the command funtion is likely to be more serious and hard to correct than an error in a numeric parameter, because it may be hard to detect, and may cause unwanted actions to occur. It would be unlikely to be corrected by the pilot without a substantial period of confusion, annoyance, and expenditure of mental resources. Accordingly, there might be a need for feedback, if there is a significant probability that the command itself might be misrecognized or misunderstood. Alternatively, the command might be entered tactually, with voice to provide the argument to the command.

Misrecognition is not the same as misunderstanding. It is possible to understand a message at a high level while at a lower level misrecognizing some of its words.

There are two ways in which the structure of a high-level message can be used to increase the probability of its being correctly understood: the probabilities for different low-level structures such as words may be changed according to higher-level expectations so that they are likely to be correctly recognized, or misrecognized words that do not fit into the high-level structure can be changed for confusable ones that do fit.

The structure of a high-level message involves everything that the higher-level protocol can use, including the situational context. For example, at a particular stage in a flight, the pilot may normally switch the map display to the more local environment. When a flight reaches this stage, the probabilities for the appropriate command may be changed within the recognizer itself, or, if the recognizer produces a nonsensical word string that might easily have been derived from a sensible one that performs the expected command, the revision might be understood to have been spoken, as suggested in Figure 9. Typically, in such a situation, the higher-level protocol would determine that the message was ambiguous or problematic, and would ask for a check of its putative

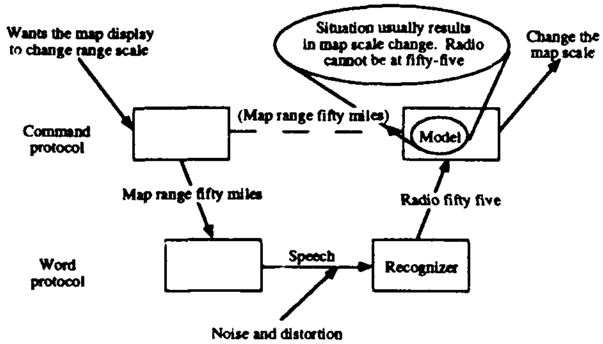

Figure 9. One way that correct understanding can come from misrecognition. The mission state normally calls for a change in the map display. The pilot speaks a command for one, but because of noise and distortion, the recognizer provides a string that would cause an illegal operation on the radio. Because there is a known possibility of this kind of recognition, plus a much higher probability for the map command than for the illegal radio command, the high-level protocol interprets the command as the one that was really intended. Naturally, this interpretation could be checked by further feedback, such as "Did you mean map display?"

understanding, or for a correction. This feedback might well be vocal.

In order to discuss the possibilities for feedback, a digression is needed on the General Protocol Grammar (GPG) that we believe underlies all dialogue. Once the GPG is understood, issues of how to choose appropriate feedback may become clearer.

The General Protocol Grammar

Many authors argue that the idea of a grammar for dialogue is absurd, and that there cannot be such a thing, because dialogue is so varied in different situations (e.g. Good, 1989). We agree, but we argue that there can nevertheless be a grammar that describes the interactions within a protocol. In fact, we argue that every protocol incorporates such a grammar, and that it is the same grammar for every protocol. For this reason, we call it the General Protocol Grammar (GPG).

We will describe the GPG in two stages. First, we treat it as a standard node-and-arc state transition grammar, as shown in Figure 10, but only for expository convenience and mnemonic assistance. A state transition grammar works under the assumption that a state is occupied until a discrete transition to a new state is made, and then that new state is occupied. In dialogue, what matters is information transmission, which does not happen instantaneously.

In the more exact approach to the GPG, the focus is on the effect of information transmission on various belief states. Changes in these belief states correspond to state transitions in the node-and-arc grammar.

The term "belief" should be taken broadly. Of course, the aircraft has no beliefs, and makes no overt deductions. It just behaves. The aircraft designer has built the contingencies in, and the aircraft has no possibility of changing them. In the Layered Protocol theory, this kind of "built-in" behavior is a property of the Coders and Decoders, whereas beliefs and deductions are among the properties of the Models. An outside observer, however, can rarely tell the difference. All the same, it seems reasonable to work as if the lower protocols tend more to "just behave," while the higher ones are more susceptible to analytic modelling that justifies the terms "believe" and "deduce." In both cases, we can use the same symbolism for the analysis.

GPG as a state transition network

A message is initiated within a protocol when the originator (O) has a chunk of information that the recipient (R) should have. The chunk may be a part of a higher-level message supported by this protocol, or it may result from some task goal on the part of O. In either case, we call it the "primal message" that the protocol is being asked to transmit. It is the job of the transmitting protocol node to determine how to transmit it, given the beliefs it has about the current situation, the history of the dialogue, the recipient's beliefs, and so forth.

At one extreme, O (meaning O's transmitting protocol node) may believe that R (the corresponding receiving protocol

node) already has the information, and will therefore transmit nothing. For example, if the goal is that the plane should fly straight and level, and it already appears to be doing so, then the "joystick protocol" should do nothing.

At the other extreme, O may believe R to know none of the message. This might be the situation associated with the entry of a flight plan into a mission database. All the information might have to be installed explicitly. As an intermediate case, the mission plan might be of a kind partly known to the aircraft, with only some elements to be explicitly transmitted, such as waypoints or regions of potential threat such as SAM sites.

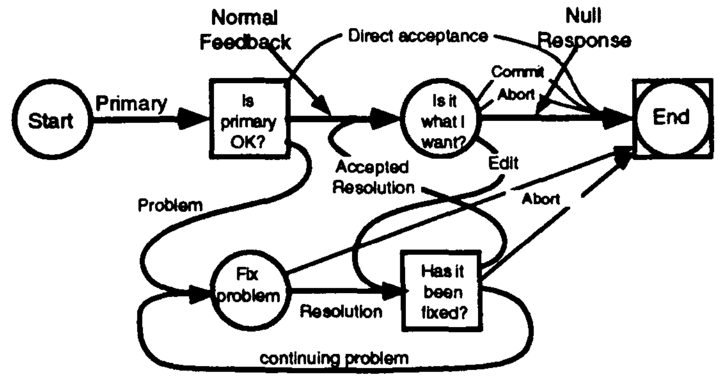

Figure 10. A sketch of the General Protocol Grammar, showing the major arcs. Circles represent stages at which the originator of the primary message must do something, squares stages at which the recipient of the primary must do something.

In the initial state of the grammar, O has some belief about what information actually needs to be transmitted, but how it is to be transmitted may be a matter for choice, especially at higher protocol levels. Perhaps O attempts to encode the whole message and transmits the encoding all at once; perhaps O transmits only enough that R is alerted to the fact that a message is being sent. In either case, what is sent is the "Primary" in Figure 10, and on receiving it R must determine whether it could represent the entire primal message. If it could, then R provides whatever feedback is necessary to get O to move to the node marked "Is it what I want." If not, R provides feedback that indicates to O that there is a problem.

Consider just these two possibilities in the case in which R's part of the dialogue is taken by an isolated word speech recognizer running with a wide open syntax. O speaks a word, and R, the recognizer, produces both a best candidate recognition and a "goodness" measure. If the recognition has a high goodness measure, then R should "want" O to move to the "Is it what I want" node at which O might accept the recognition as correct. Otherwise, R would want O to move to the "Problem" node at which O could solve the problem. Clearly, these two situations demand distinct feedback so that O can determine which possibility R intends. But most recognizers that provide word-by-word feedback do not indicate any difference between high-probability and low-probability recognitions. O can find the problematic ones only by monitoring each word fed back. If the errors are few, as they often are for good recognizers, O is likely not to detect them. But almost certainly, errors will be more probable for the recognitions given a low goodness measure by the recognizer than for those given a high goodness measure. There may be occasional errors even in the recognitions "believed" by the recognizer to be good, but it will be hard for the user to detect them among all the good ones. They are probably best passed through to a higher protocol for detection and correction.

This analysis suggests the reason for a practice that is commonly found useful: to feed back only those words with a low goodness measure, and to accept the rest silently, passing them up to a higher level as if they were correct. O can then readily detect R's use of the "Problem" arc in the grammar, and can make appropriate corrective or accepting responses. An additional benefit is that R should not expect any response to the well recognized words, but should expect a confirmatory or corrective message about each potential misrecognition. O is thereby relieved of the need to identify for R which word is being corrected, as O would have to do if R reported each word. There is a double benefit for the resource loading on O: the monitoring of feedback for incorrect words is eased, and O has less to do to correct a false recognition.

In the GPG, the different arcs may be instantiated in different ways, depending on what the partners believe each other to believe. For example, suppose that R (in any protocol, not just word recognition) believes that the primary message has provided enough information to permit a satisfactory interpretation of the primal message. R wishes O to move to the node "Is it what I want" in Figure 10. If R believes that O will be sure that R did get a good message and would interpret it properly, then no overt feedback is necessary. We call this a "null instantiation" of the Normal Feedback arc. A second possibility is that R believes that O does not know whether R has made a good interpretation, but would trust R's judgment in the matter. All R need do is to indicate that the message was received. We call this a "neutral instantiation" of the Normal Feedback arc. There are at least two other instantiations for this arc, "informative" and "corrective"; most arcs in the GPG have more than one instantiation.

The state transition description of the GPG is in principle adequate for many purposes. In its full form, there are many more arcs than are shown in Figure 10—about 24 arcs in one recent version, with an average of about two instantiations for each arc. But a state transition diagram is inadequate for real communication, in which partial interpretations are continuously being made at all protocol levels. To handle this situation, we must consider the models and beliefs that underlie the state transition description of the GPG.

Belief structure of the GPG

The GPG is a description of the process of communicating a virtual message. It is not concerned with the content or level of abstraction of the message. Accordingly, the information that directs the state transitions is concerned not with the

message itself, but with the satisfaction of the partners about its transmission.

We identify three propositions dealing with the message transmission:

- P1: R has made an interpretation of the message.
- P2: If P1, then R's interpretation is satisfactory.
- P3: it is not worthwhile to continue trying to transmit the message.

These three propositions are statements of fact. Facts are unknowable, but anyone is entitled to believe them with any degree of certainty from strong disbelief through total ignorance to implicit faith. We assign the degree of belief that someone has about one of these facts a number from -1 to +1. We notate the degree of belief A holds about P as A(b,P), or simply A(P), omitting the b because by default we are dealing with belief. On other occasions we use a similar notion for the strengths of goals and intentions, using g or i, which are ordinarily not omitted in the notation.

The final element of notation is to divide the degrees of belief into five categories, as a matter of convenience rather for any reason of theory: Disbelief (D), Negative belief (N), ignorance (X), weak belief (W), and Strong belief (S). The letters correspond to numerical ranges that are not well specified. The boundaries between the ranges occur at points where the behaviour of one or other partner may change.

Given this notation, we can write statements such as W<A(P), which, by convention, means that A holds at least a weak belief in P, or S=A(b,W<B(P)), which means that A strongly believes that B at least weakly believes P. S=A(g,W<B(P)) means that A holds a strong goal that B should at least weakly believe P.

Now consider the three propositions of the GPG. So long as a message is still being transmitted, each partner must at least weakly believe that P3 is false:

- W<O(b,¬P3) & W<R(b,¬P3)

Implicit in this is that at least one of the partners believes that either P1 or P2 is false and that each has a goal that both P1 and P2 should become true.

This notation may seem a little removed from the problem of flying an aircraft, but let us apply it to the simple matter of adjusting the climb angle, using the joystick. We shall call the pilot C (commander) and the aircraft A.

The design of the aircraft suggests that both A and C "believe" that P2 is always true (in the absence of malfunction). In other words, if the pilot manipulates the stick appropriately, the aircraft will assume the correct attitude. But the variety of flight situations assure that simply setting the joystick to some condition for a fixed duration will not work. The pilot must receive feedback from the aircraft as to its present (and perhaps predicted) attitude. This is normally done through an instrument display in current aircraft, though in earlier days the pilot had to look outside. We can take the instrument display as feedback for the joystick message.

In the state transition diagram of the GPG, the behavior is only crudely described. The pilot makes an initial adjustment ("primary"), the plane assumes some attitude ("Normal Feedback"), the pilot determines whether it is the desired attitude, and if not, uses the "Edit" arc followed by "Accepted Resolution" as the plane assumes a new attitude. The "Edit" loop is continued until the attitude is correct.

Such discrete control is a very poor way to handle an aircraft. Effective control is continuous, the pilot judging the attitude and the rate of change of attitude, and manipulating the joystick continuously to achieve as quickly as possible the perception that the attitude is correct. The protocol feedback loop and the types of message involved are shown in Figure 11.

In terms of the belief structures, the pilot starts with a strong belief that the aircraft has not interpreted his intention that it take some particular attitude

- S=C(¬P1)

The aircraft has no belief, as the word is ordinarily used in English, since models are not built-in to most aircraft, but a future computer-controlled aircraft might well develop some beliefs. In fact, one might consider that the Mulhouse A-320 crash as being due to a belief held by the aircraft that differed from the intentions of the pilot about the future path of the plane. Whether or not this is the case, one can in the formalism assert that by design, if the pilot moves the joystick the aircraft "believes" that it holds the wrong attitude. Hence, the joystick movement leads to:

- S=A(P1 & ¬P2)

It has interpreted (and acted upon) the message (joystick movement) but "believes" its interpretation is incorrect because the joystick continues to be moved.

As the aircraft's attitude approaches the desired one, the pilots's belief structure changes, so that strong belief in the wrongness of the attitude gives way to weak belief, indifference, and disbelief. At that point, the joystick is neutralized, so that the aircraft can now "believe"

- S=A(W<C(P3))

and hence

- S=A(W<C(P1 & P2)).

The aircraft "deduces" from the pilot's cessation of moving the joystick that the pilot is satisfied with its interpretation of

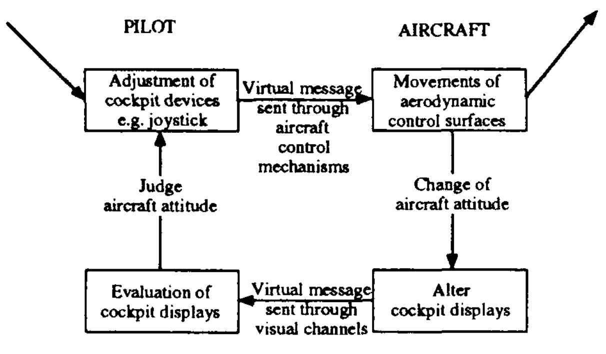

Figure 11. The protocol loop for the control of aircraft attitude. The pilot sends a continuous stream of messages by manipulating the joystick and other controls, which are sent by means of whatever control mechanisms the aircraft provides (cables, hydraulics, computer-driven servos) to the aerodynamic control surfaces. The aircraft signals the interpretation of this message by means of changes to the cockpit displays.

the message, which is to say that he is satisfied with its current attitude.

It is important to note that the changes in belief are continuous, and occur in parallel with the actions of both partners—the pilot and the aircraft. It is this continuously developing and parallel communication that cannot be handled by the state transition description of the GPG. Neither can it be handled by a turn-taking analysis of dialogue. It is, however, characteristic of most realistic communication, whether among people or between people and their "intelligent" machines.

Voice and belief structure

When we come to consider voice interaction, the concepts of "belief" and "deduction" become more plausible, since voice recognition equipment is normally based on probabilistic models. The recognizer starts with some set of expectations about the possible things the user might say, and these expectations often include probabilities that might well be situation-dependent. In the LP structure, the probabilities will depend also on the momentary state of interpretation of the higher-level message that it supports.

Let us suppose that the higher level message is a flight plan consisting of a set of waypoints identified by name from the hypothetical map in Figure 12. Let us also suppose that the aircraft is "intelligent" in that it has a database of locations and some concept of what a normal flight plan might look like. In particular, a normal flight plan does not double back on itself. Now the pilot starts to enter waypoints: Astal, Birland, Demick, Coltaine, Endow.

Suppose the pilot makes a mistake and enters Demick before Coltaine. The recognizer correctly identifies the words from the acoustic signal. The protocol at the next level translates these words into coordinate strings that will be entered into the navigation system. But the Model in this protocol could incorporate the knowledge that normal routings do not include consecutive turns near 180°, and this knowledge would allow it to propose that the message is possibly incorrect. In the state transition grammar, the aircraft would use the "Problem" arc in Figure 10. In the belief notation,

- W<A(P1 & ¬P2 & W<C(P1 & P2))

which indicates a difference between its view of the correctness of the message and the view it believes the pilot has. The result should therefore be to inform the pilot not only that it finds the message dubious, but also in what way it finds it dubious. Accordingly, its feedback should be to propose a reasonable reinterpretation: "Do you mean Birland, Coltaine, Demick?" The pilot, of course, might have intended the zigzag route that was originally entered, and could say so, by voice.

None of the above indicates the manner in which the feedback is provided. There are some criteria that could help to determine that; the method must alert the pilot that the feedback exists, and it must be able to convey the information as to what the problem might be. It cannot, therefore, be provided by a non-obvious visual display, unless the probability of error is high enough that the pilot will normally look to see whether one had occurred. If such is the case, the same display could support feedback from both the word recognizer protocol and the waypoint construction protocol.

Integration

The idea of "integration" is closely bound with that of diviplexing, but the integration of voice with non-vocal interaction between pilot and aircraft usually does not involve diviplexing at any low level. The voice usually replaces rather than supplements the non-vocal interactions, though it could affect the interpretation the aircraft places on non-vocal actions. For example, a navigation display might be presented on a touch-sensitive screen, and the area displayed changed under voice control. Likewise, normally the non-vocal interactions do not supplement the voice. Each acts essentially independently, except that they both affect the behavior of the aircraft.

Consider the waypoint entry example illustrated in Figure 12. Suppose the plane were on the leg Coltaine-Demick and the pilot spoke a command such as "Next waypoint Birland." The flight situation would allow the waypoint protocol Model to determine that this would entail a turn near 180°, and might suggest the possibility of a misinterpretation that should be queried. This query would be independent of whether any waypoints had previously been entered by voice, but would be based on the present situation of the aircraft.

Another way in which the different modes of interaction relate to each other is that each imposes a load on the pilot's resources. The pilot must be kept aware of the local situation, and alerted to possible dangers and opportunities, but to provide too great a flood of information would risk the pilot ignoring important events. The problem of evaluating situation awareness and workload is a long-standing one in psychology, and no solution is near. Nevertheless, qualitative analyses could easily assist the interface designer in determining how and when to provide feedback or to request pilot action.

If a particular interaction would benefit from joint use of the symbolic information transmitted by voice and the continuous information transmitted by control movements, the structure of the messages that immediately support the high-level message must contain the information that allows them to be

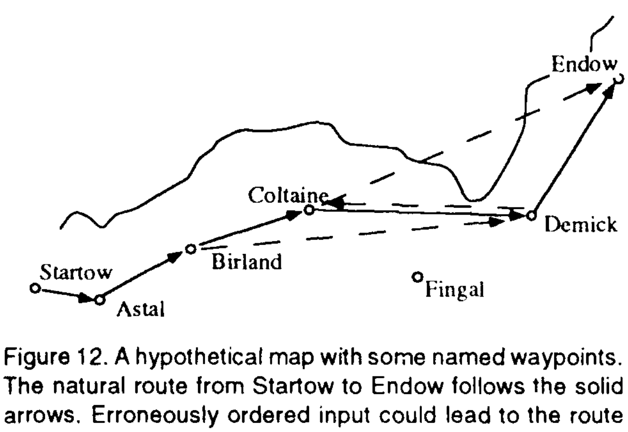

Figure 12. A hypothetical map with some named waypoints. The natural route from Startow to Endow follows the solid arrows. Erroneously ordered input could lead to the route shown by dashed arrows.

recombined. For example, a map display contains labelled entities that could well have descriptive information available in a database. The geographic spatial information is well displayed pictorially, and the items can be selected verbally, but the notion of "SAM sites north-east of Demick" involves a linkage between the verbal and the visual, through the coordinate location of Demick, which is at once symbolic and selected from a continuum of possible locations.

CONCLUSION

A basic principle of behavior is that purposive actions can be performed only with respect to some percept that the actions will affect, based on sensory data. A natural corollary, which leads to Perceptual Control Theory (PCT), is that actions are normally such as to make the percept closer to some desired state, or reference percept. Behavior thus controls perception.

PCT contains the concept of an Elementary Control System, a structure that accepts sensory input from a variety of sources, combines them into a percept through some perceptual function, compares the percept with a reference to create an error signal, and distributes some function of the error signal to effectors. Both the sources of sensory data and the effectors may well be themselves Elementary Control Systems at a lower level in a hierarchy, so that the reference signal in any Elementary Control System is a combination of the error signals from higher ones. The perceptual control system as a whole consists of many layers of Elementary Control Systems, the lowest ones acting directly on, or receiving data directly from, the physical world.

The theory of Layered Protocols asserts that a similar structure describes the interactions among "intelligent" entities, which are entities that have three independences: independence of design, independence of sensing mechanism, and independence of action. Messages are passed by means of creating effects in the physical world, but the physical messages represent messages of a hierarchy of levels of abstraction. The passage of a message at any level of abstraction uses a specific protocol, which includes a general protocol grammar (GPG) that determines the kinds of feedback that are appropriate to different conditions in the sending of the message.

The GPG can be applied to the manual control of an aircraft, as well as to both simple and complex voice interaction. The problem of integrating voice with other control mechanisms thus becomes partly one of determining which kinds of message suit the symbolist character of voice, and which suit the continuous character of manual control. In aircraft, the second issue of integration is less important: how to ensure that a high-level message transmitted by voice and manual control is properly reintegrated by the aircraft. Mission situation can be effective in determining the interpretation of high-level messages supported in part by voice, even when the recognizer correctly reports words erroneously spoken by the pilot.

Layered Protocols provides a principled framework for describing and integrating messages of different kinds, especially in complex interfaces such as the aircraft cockpit.

NOTE ADDED AFTER THE SYMPOSIUM:

Graceful control of automated systems

On the first day of the workshop, several talkers made the point that pilots had a difficult time accepting automated functions beyond the most simple, although they indicated in questionnaires that they wanted them. What the pilots did not want was for the automated functions to take decisions at critical moments that they would rather take for themselves, although the automated function could perform non-critical duties. This problem seems to be readily addressed within the PCT framework.

Both the plane and the pilot are conceived as hierarchic control systems, the plane's upper-level references being set either by the designer or by the pilot. For examples, the pilot gives the autopilot a reference to keep the plane on a certain heading at a certain altitude and with a stable attitude regardless of winds. The pilot resets this reference from time to time, or she might set a whole sequence of waypoints from which the plane computes references for the autopilot. In either case, if we think of the pilot and plane as one single hierarchic control system, the plane's chunk simply takes over the function of performing the task of satisfying the references provided by the pilot.

If the pilot has delegated control, the plane taking over the particular function, the pilot tends to lose "situation awareness" in respect of that function. He could control the function if he wanted to, but since he is not, neither is he acquiring the sensory information that would allow him to get the perception that he could be controlling. He may not perceive what is going on. The pilot's re-acquisition of situation awareness when retaking control of an automated function is a significant problem. To continue the autopilot example, the autopilot is switched out of the control loop, and the pilot's own lower-level control systems take over the maintenance of heading, altitude, and attitude. One significant case in which this might happen is collision avoidance, where situation awareness is critical.

The view of the automated function being switched in or out of the loop in alternation with the equivalent part of the pilot's hierarchy, as in Figure 13, is almost inevitable with conven-

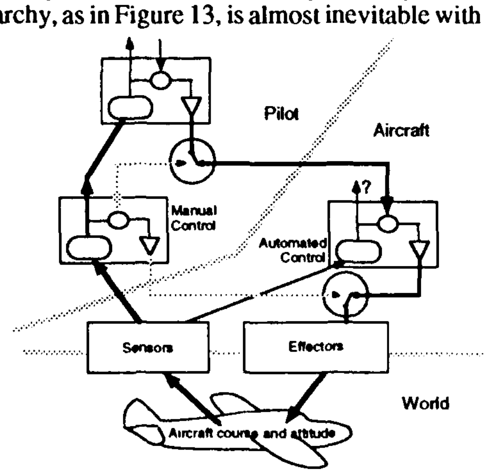

Figure 13. Conventional switched mode of operation of automated functions. When the aircraft is controlling a function, the pilot is not.

tional approaches to the problem. But PCT offers a different solution. Imagine that instead of a simple switch that sends a reference signal either to part of the plane's hierarchy or to part of the pilot's, the reference signal is sent always to both, as in Figure 14. If the pilot is choosing not to control, the gain in her part of the loop is zero. The gain in the aircraft's part of the loop is adequate to maintain course against external disturbances.

But it is possible for the pilot to set his gain to some low value other than zero, and "shadow" the aircraft's control. The aircraft could sense this in two ways. One way is that the pilot's attempts to control might set up a conflict in the lower-level systems that actually drive the plane's control surfaces. The result would be a persistent failure of the automated system to achieve the desired percept, if the pilot's references differed from those of the plane. The second is that in contrast to ordinary disturbances, the pilot's actions can be directly sensed by the plane, as shown by the dashed arrow in Figure 14. So long as the pilot's gain remains low, the automated system would keep its own gain high, but as soon as the pilot's gain increased, the plane would drop the gain of the automated system, perhaps to zero. The pilot is, at low gain, maintaining situation awareness, or regaining it preparatory to taking control.

There is a continuum, as the plane's gain decreases, between the plane performing the function, assisting (and perhaps training) the pilot to perform it, and getting out of the way to let the pilot do what she wants. There is no need for the pilot to switch automated functions in and out; they are in by default, but as soon as the pilot starts controlling what they control, they gracefully get out of the way.

What the pilot can switch in or out, or alter in a continuous way, is the sensitivity of the plane to the pilot's insistence on control. A novice pilot could set a high level, asking the

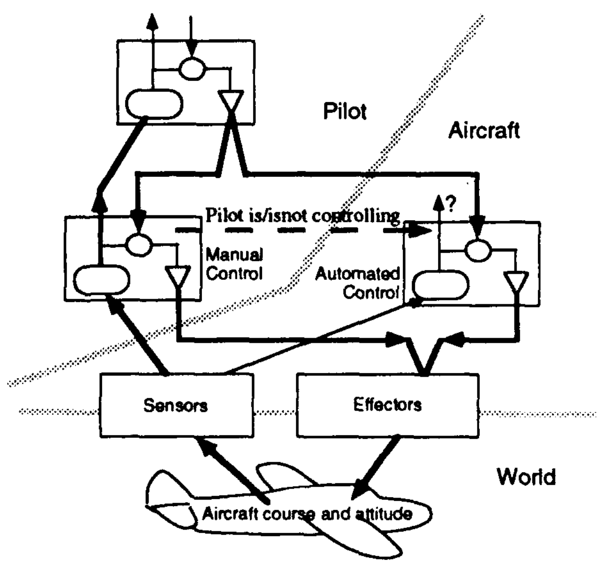

Figure14. A PCT-based view of conjoint manual and automated control. The automated system maintains control until it senses that the pilot is controlling the "same" percept, when it reduces its gain or even stops entirely, until the pilot ceases attempting to control that percept. At low gain, the automated system can assist or train a novice pilot.

plane to do what it thinks proper even though she requires it moderately strongly to do something else, whereas an expert would want it to get out of the way as soon as she started controlling.

Shifts of control locus need affect only a small part of the control hierarchy. The pilot's choice to control the course of the plane does not indicate that he must control the positions of individual control surfaces. And the plane can know at what level the pilot does desire to take control. The pilot may, for example, take quick evasive action (controlling the momentary attitude and course of the plane) while leaving the automated systems in charge of the control surfaces and the attainment of the waypoints that define the larger course of the plane.

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NOTE

This paper owes much to discussions over several years within NATO AC243 (Defence Research Group) Panel 3 Research Study Group 10 on Automatic Speech Processing, and to electronic interactions with W. T. Powers and other participants in the Internet mailing list CSG-L.

Discussion

QUESTION R.M. TAYLOR

Your description of the application of perceptual control theory to the control of the aircraft's state seems clear and useful. However, the designer's main task in the future will be to help the pilot to solve mission problems. Can you forsee any changes to perceptual control theory that will be necessary in order to apply it to solving mission tactical problems and pilot tactical decision-making?

REPLY

Perceptual Control Theory (Powers, 1973) has many different kinds of abstraction - eleven at the current state of the theory, including categories, sequences, programs, principles, among others. Mission problems seem related to programs and sequences, which are components of current theory, so to that extent no changes are necessary. On the other hand, the precise behaviour of non-linear control systems is not well understood and neither is the behaviour of neural network meshes, which form a part of the control network. Hence the theory is likely to provide a framework for productive analysis and design rather than a precise predictive model. The key point is to realise that the stabilities of behaviour relate to the intentions of the actor and not to the actions taken to realize those intentions.

G-LOAD EFFECTS AND EFFICIENT ACOUSTIC PARAMETERS FOR ROBUST SPEAKER RECOGNITION

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ABSTRACT

The aim of this study was to find, from the computer signal analysis, acoustic features of the speech production with G-load effects. Their correlates with physiological features will permit a interpretation of the variability of formant and pitch shifts.

The pilot study experiments were conducted by SEXTANT and the LAMAS (Laboratoire de Medecine aérospatiale) du centre d'essais en vol de Bretigny. Six subjets participated in the experiment. Their mean age was 30 years. A series of experiments in centrifuge environment have been performed as part of a research program.

A specific vocabulary has been made for the first investigation with speakers in centrifuge. Comparison of spectrographic analysis and wavelet decomposition have permited to show a spectral pattern modification for recognition process.

Due to the accuracy and limitations of the sono-graph measurements, we have developed multiresolution transforms. A window Fourier transform is better suited for analysing signals where all patterns appear approximately at the same scale.

The old multivariate statistical analysis, after the Bark's transformation, can produce a good projection on the eigenvectors of the correlation matrix. The choice of the eigenvalues seems very easy for seeking the best representation of speech production.

An interpretation of the mechanical effects due to the acceleration can been shown with analysis tools. We observed, in agreement with acoustic multi resolution analyses, that producing speech in G-load conditions can increase energy, pitch and formant frequency locations. The influence of the breathing on some parameters is noticeable.

The last section of the paper discusses the incidence of these results on the robust speech recognizer for military cockpit environment.

RESUME

Le but de ce travail était de décrire les modifications de l'élocution sous facteur de charge à partir d'outils d'analyse. Leurs corrélations avec des effets physiologiques permettent de fournir une interprétation de la variabilité formantique et du décalage de la fréquence fondamentale des voisements.

Une expérimentation a été menée conjointement entre SEXTANT et le LAMAS (Laboratoire de Medecine Aérospatiale). Six sujets d'âge moyen 30 ans ont participé aux expérimentations en centrifugeuse.

Un vocabulaire spécifique d'évaluation a été mis au point, des tests ont comparé les sonogrammes classiques aux décompositions sur des bases d'ondelettes orthogonales et continues.

En raison de la précision et des limitations inhérentes au sonogramme, nous avons développé des transformations multi-résolution. Le choix de l'analyse de Fourier se révéle en effet judicieux uniquement lorsque les phénomènes à analyser ont la même échelle et sont à structure harmonique.

L'analyse multi-variable en composantes principales après transformation de Bark a permis de mettre en évidence des disparités en comparant les projections sur plusieurs vecteurs propres de la matrice des corrélations. Le choix des valeurs propres semble aisé et concourt à la visualisation exhaustive de la production vocale.

Une interprétation des effets mécaniques liés à l'accélération a été possible grâce aux outils mis en place. Nous avons observé conformément à l'analyse multi-résolution une augmentation notable de l'énergie, de la fréquence du fondamental et de la variabilité formantique. L'influence de la respiration fait partie des indices pénalisant la prosodie donc la reconnaissance.

La dernière section traite de l'incidence de ces résultats sur le durcissement d'un système de reconnaissance pour avion d'armes.

I) Conditions environnementales

En reconnaissance automatique de la parole, les taux de reconnaissance obtenus pour des applications "laboratoire" ne sont pas directement transposables aux environnements difficiles, type avion d'armes. La chute des scores de reconnaissance s'explique, non seulement par la présence de bruit, mais également par la variabilité acoustique induite par le locuteur pour s'adapter aux contraintes environnementales.

L'amélioration des performances des systèmes de reconnaissance en conditions réelles passe par une meilleure compréhension des facteurs dimmensionnants; en raison de la multiplicité des conditions d'utilisation des systèmes opérationnels la description exhaustive des différents paramètres constitue une lourde tâche.

Nous avons voulu au cours de ce travail, étudier les incidences du facteur de charge pris isolement sur la production de parole et par delà sur le système de reconnaissance en vue de dégager un durcissement de l'algorithmie du système global.

Le panorama des travaux réalisés à ce jour sur la parole sous facteur de charge parait restreint; nous décrivons les effets de l'accélération sur les paramètres acoustiques de l'élocution. Afin de mieux analyser les résultats de la campagne d'essais nous avons développé une série d'outils discriminants.

Nous élaborons par la suite une méthodologie expérimentale pour mettre en évidence l'influence du facteur de charge sur la production de parole. Nous donnons pour finir une interprétation des effets mécaniques. Nous montrons l'utilité d'une detection automatique de parole fiable et robuste associée au système de reconnaissance proposé.

La communication verbale s'articule suivant diverses étapes qui relient le concepteur du message au cerveau de l'auditeur. Le premier est de niveau linguistique il correspond aux choix des différentes unités signifiantes par le locuteur; le niveau suivant est articulatoire, le processus d'encodage se termine par la production d'une onde sonore.

La nature très particulière des enregistrements réalisés pendant des décennies dans des conditions dites de "laboratoire" a conduit un grand nombre de spécialistes à proposer une interprétation incompléte de la variabilité acoustique et à rechercher des invariants.

En effet pour certains auteurs, la variabilité acoustique est présentée comme la résultante passive des différences morphologiques entre individus; elle est considérée hors de l'organisation linguistique.

Si cette interprétation peut s'appliquer à l'analyse de la parole classique, elle ne parvient nullement à expliquer les modifications majeures qui apparaisent pour l'élocution en ambiance sévère : pour un même individu la valeur formantique est fortement versatile et tributaire de l'effet Lombard.

Ces écarts acoustiques ne sont interprétables que si l'on admet qu'ils résultent de facteurs actifs liés aux stratégies d'adaptation et/ou de compensations articulatoires mises en oeuvre en situation réelle.

Les pilotes, pour augmenter leur tolérance au facteur de charge effectuent différentes manoeuvres de tension (appelées manoeuvres anti-G). Ces efforts de tension musculaire et d'expiration forcée résultent de la combinaison de trois exercices spécifiques :

- pousser la tête vers le bas entre les épaules pour réduire la distance coeur-oeil,
- tendre au maximun les muscles abdominaux,
- augmenter la pression intrathoracique par la méthode d'expiration forcée. Ces manoeuvres modifient notablement le pattern respiratoire [2].

La variabilité acoustique porteuse d'informations linguistiques a pour origine :

- des facteurs inter-individuels,
- des indices intra-individuels,
- l'instabilité de l'environnement,
- l'omniprésence de fluctuations aléatoires.

Les capacités de décodage de l'Homme intègrent ces sources de disparités qui, loin de constituer une gêne permettent, au contraire, de maintenir l'intelligibilité du message vocal en dépit de circonstances parfois difficiles. Cet aspect pénalise cependant un sytème de reconnaissance avec apprentissage préalable, fonctionnant à partir d'une méthode globale.

Le référentiel des accélérations permet de traduire les conséquences physiologiques des efforts en fonction de leurs directions par rapport aux axes du corps. La plupart des manoeuvres aéronautiques s'accompagnent d'accélérations + Gz, principalement en mission de combat, les accélérations Gx sont modérées (excepté le décollage catapulté), quant aux accélérations Gy, elles sont quasiment inexistantes [1].

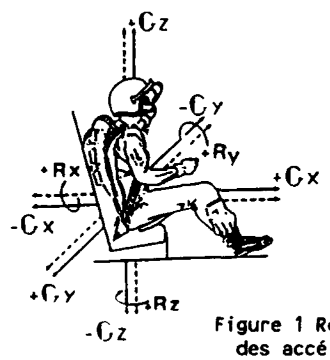

Figure 1 Referentiel des accélérations.

On peut penser qu'en phase inspiratoire l'accélération Gz va s'opposer aux mouvements d'élévation en avant des côtes : le volume inspiré risque d'être diminué.

Lors de l'expiration, l'accélération va faire descendre plus rapidement la cage thoracique, le diaphragme aura tendance à s'abaisser par rapport à sa position nominale.

Il existe à notre connaissance que peu de travaux traitant du problème de l'élocution sous facteur de charge. Les difficultés expérimentales posées par la contrainte accélérométrique et la combinaison du facteur de charge à d'autres paramètres (bruit élevé, masque à oxygène, stress..) en sont sans doute la cause. Les travaux significatifs sont ceux de l'Armstrong Aerospace Medical Research Laboratory (AAMRL) [3].

II Moyens d'analyse

Nous avons recensé 4 grandes familles d'outils :

- les méthodes fréquentielles (brute, apodisée par Hamming, calcul des moments spectraux, sonogrammes "bande large" et "bande étroite").
- les analyses multi-echelles (ondelettes orthogonales à support compact, ondelettes continues).
- les décompositions cepstrales (estimation du pitch, détection des voisements).
- l'analyse statistique multi-dimensionnelle (matrice des corrélations sur une échelle de Bark, projections sur la base orthogonale des vecteurs propres).

II.1) Décomposition fréquentielle

L'analyse de la parole fut depuis ces premices régie par la discrimination spectrale. Le formalisme établi à la fin du siècle dernier a suivi une évolution, surtout dans sa transcription physique, analogique au début, numérique ces dernières années.

Il n'en demeure pas moins que le problème de l'analyse du signal vocal de part la nature non stationnaire du phénomène se révèle délicate. L'utilisateur souhaite en effet avoir à la fois, une bonne discrimination temporelle (plosives, fricatives) et une grande résolution fréquentiellle (analyse formantique des noyaux vocaliques).

Cette problématique s'apparente à la relation d'incertitude d'Heisenberg de la mécanique quantique : le produit de la mesure de la position et de la quantité de mouvement d'une particule est bornée. Ce dilemme résidant dans la necessaire augmentation de la bande (précision en distance) incompatible avec un allongement de la tranche temporelle (précision en Döppler).

Depuis la fin des années soixante, des algorithmes de calcul rapide (Cooley-Tuckey) ont permis de généraliser la Transformée de Fourier.

Cette base orthogonale d'exponentielles se révèle excellente en discrimination fréquentielle mais très mal localisée en espace (ou en temps).

L'apodisation de la tranche d'observation est souvent nécessaire pour une bonne réjection de l'effet parasite des lobes secondaires. La résolution fréquentielle à -3 dB est de l'ordre de l'inverse de la tranche d'analyse et peut-être relaxée par l'utilisation de l'adaptativité du lobe de directivité (Algorithme de Capon).

Corrélativement, les fonctions orthogonales de Haar (fonctions binaires) possèdent une bonne localisation temporelle au détriment d'une discrimination fréquentielle médiocre.

La problématique d'analyse peut se résumer ainsi : à partir d'un vecteur réduit de combinaisons linéaires d'entrées, il s'agit de trouver un produit scalaire (définissant ou non une base orthogonale) et sa norme associée, *qui discriminent au mieux* à la fois les explosions temporelles, les structures harmoniques et leur déplacement sous facteur de charge.

L'analyse temps-échelle (proposée par J. Morlet [4]) permet de suivre le signal à différentes échelles à l'aide d'une fonction analysante mère $\Psi_{a,b}$ (appelée aussi "ondelette"); cette fonction est paramétrée par un coefficient de dilatation a et un paramètre de translation b. Cette décomposition dont le formalisme généralise les transformées déjà citées permet la décomposition du signal sur des bancs de filtres spécialement crées pour une analyse déterminée.

Depuis près de deux siècles le formalisme des séries de Fourier a permis de décomposer tout signal périodique en une somme de fréquences pures (coefficients de Fourier, spectre discret). Pour les phénomènes quelconques l'intégrale de Fourier étend cette représentation temps-fréquence.

Cette transformée est égale au produit scalaire pour toutes les valeurs du temps, du signal s(t) par la fonction exp(-j2πft), il vient pour le spectre continu d'amplitude :

$$S(f) = \lim_{T \to \infty} \frac{1}{T} \int_{-T/2}^{+T/2} s(t) . e^{-j2\pi ft} \, dt$$

Cette représentation physique ne peut pas être évaluée systématiquement de part la présence de l'intégrale qui s'avère parfois difficilement calculable. On a recours alors à une approximation discrète qui contient la même information que le spectre continu, sous réserve que le signal soit à spectre borné (*interpolation de reconstruction exacte*). La transformée de Fourier discrète d'un signal x(k) s'écrit alors :

$$X(f) = \sum_{k=-\infty}^{k=+\infty} x(k) . e^{-j2\pi fk}$$

La fonction X(f) est périodique, de période fe et est généralement une fonction complexe de la variable réelle f. Bien qu'utilisable en l'état, la vulgarisation de cette analyse est due à des algorithmes rapides (FFT : Fast Fourier Transform) qui réduisent le coût CPU de N^2 opérations à N/2 $\log_2$ N. L'expression de la transformée rapide est donnée par :

$$x(k) = \frac{1}{N}\sum_{n=0}^{N-1} X(n).\exp(-j2\pi\frac{nk}{N})$$

avec k = 0, ..., N-1

La parole étant un signal scalaire réel quelconque, sans nécessité de réduction de débit par démodulation complexe, il en résulte une symétrie hermitienne sur le spectre d'amplitude (partie réelle paire, partie imaginaire impaire).

La prise en compte du seul module conduit à perdre une partie non négligeable de l'information, il est difficile en effet de gérer convenablement le modulo 2π de la phase.

Pour établir des éléments de comparaison entre les diverses analyses proposées nous avons pris comme structure temporelle une tranche de 25,6 mS à évaluer toutes les 12,8mS (fe=10 KHz, fc=4,8 KHz).

Nous donnons figures 2 et 3 un exemple de spectre court terme (élocution "Radar" à 1,4G) obtenu par une analyse de Fourier pondérée, préaccentuée ou non par filtrage numérique non récursif du premier ordre.

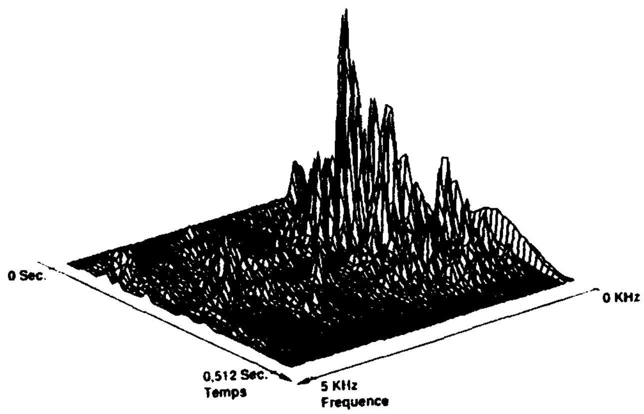

Figure 2 Analyse Temps-Frequence court terme 3D.

Nous résumons tableau 1 le nécessaire compromis entre élargissement du lobe principal et niveau des secondaires acceptable.

La nécessité du filtrage amont préaccentuateur est, au vue des tracés, manifeste pour rééquilibrer l'énergie spectrale qui en situation calme à tendance à se localiser autour de 800 Hz. Les noyaux vocaliques sont stables et clairement mis en évidence par ce type d'analyse.

Paramètres \ Fenêtrage	Rectangulaire	Hamming
Niveau plus haut secondaire	- 13 dB	- 43 dB
Décroissance des lobes secondaires	- 6 dB/oct	- 6 dB/oct
Gain cohérent	1	0,54
Bande de bruit équivalente	1	1,36
Ouverture à - 3 dB	$0,89 . T^{-1}$	$1,3 . T^{-1}$
Ouverture à - 6 dB	$1,21 . T^{-1}$	$1,81 . T^{-1}$

Tableau 1 : Eléments de comparaisons des pondérations.

La figure 3 visualise la même élocution que précédemment sans effet du filtrage en tête, l'énergie est alors typiquement concentrée dans les basses fréquences.

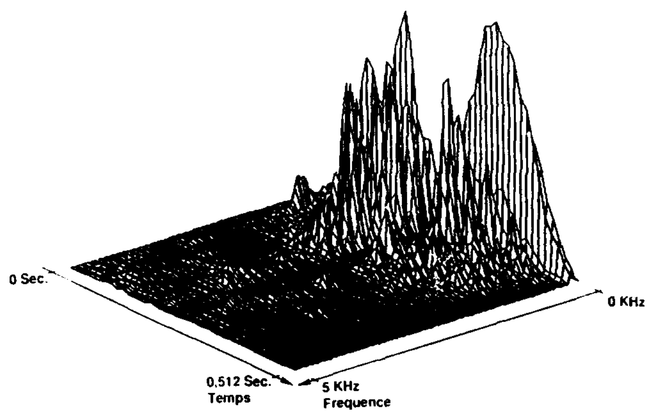

Figure. 3 : Spectre temps-fréquence court terme 3D.

II.2) Analyse formantique

Pour mesurer la répartition énergétique (essentiellement autour des formants), une approche dans l'estimation de cette fréquence moyenne, consiste à former le périodogramme moyenné, soit :

$$S_{xx}(f_i) = X(f_i).X^*(f_i)$$

avec f_i = ik/M

où X(f) représente le spectre d'amplitude et $X^*(f)$ son conjugé.

En assimilant la densité spectrale de puissance à la réalisation d'un processus stationnaire, il est possible de calculer alors les moments normalisés et en particulier la fréquence quadratique :

$$\hat{f}2 = \left(\frac{\sum_{i=0}^{N-1} fi^2 . Sxx(fi)}{\sum_{i=0}^{N-1} Sxx(fi)} \right)^{1/2}$$

Les positions peuvent être alors évaluées dans des bandes pré-établies et multiples du pas des canaux de FFT (Δf = 39,06 Hz); la sommation est faite sur [k1,k2] et non pas [0,N-1].

La position de la bande de bruit biaise d'autant l'estimation des formants ; pour éliminer ce biais, il suffit de remplacer $S_{xx}(f)$ par:

$$Ss(f) = Sxx(f) \quad \text{lorsque } Sxx(f)max./Sxx(f) < K$$
$$= 0, \quad \text{ailleurs.}$$

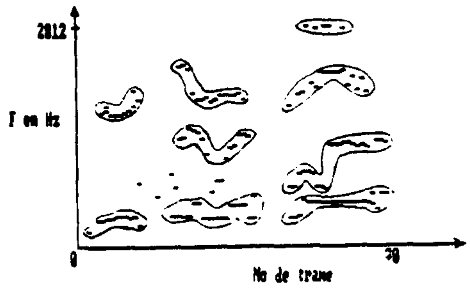

Figure 4 : Déplacement formantique sous accélération ("Display Waypoint", 5G)

II.3) Sonogramme linéaire

Les outils précédemment explicités relévent tous d'une prise d'information temporelle par fenêtre glissante avec recouvrement de moitié. Cette longueur doit être de dimension suffisante pour une estimation et un échantillonnage satisfaisant du fondamental. La qualité de la pondération est beaucoup moins importante que la largeur de cette fenêtre d'analyse, surtout pour une bonne estimation de la position fréquentielle des formants. Une façon élégante de visualiser ces structures harmoniques consiste à tracer un sonogramme décrit par le synoptique figure 5.

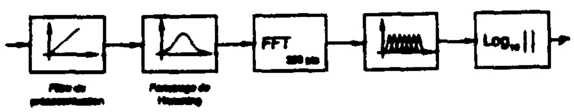

Figure 5 : Décomposition du Sonogramme

Le fenêtrage triangulaire conserve la structure linéaire à la décomposition, la largeur des bases fixe le type d'analyse (Large bande Lb= 450 Hz, bande étroite Lb= 45 Hz). Les figures 6 et 7 fournissent un exemple de sonogramme pour l'élocution "Display" dit par un homme ou une locutrice.

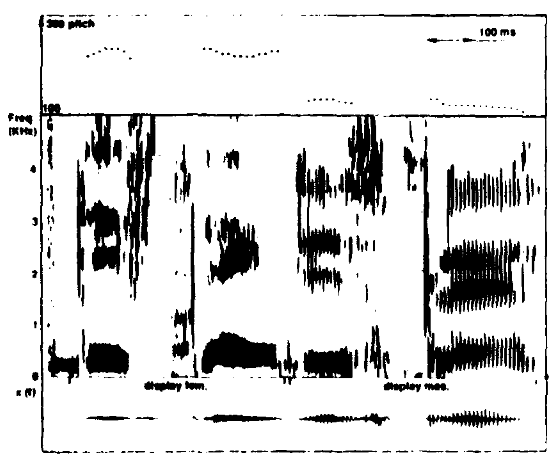

Figure 6 Sonogramme Bande Large

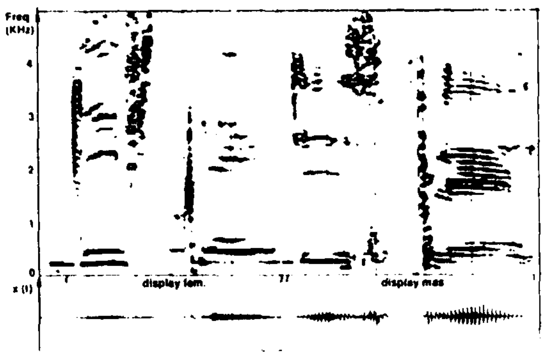

Figure 7 : Sonogramme Bande Etroite.

Ce type de visualisation met en évidence les structures voisées du "i" et du "ay", la sifflante "s" est bien localisée en haute fréquence (pattern caractéristique), alors que la plosive "p" trés courte sur le tracé temporel occupe l'ensemble des canaux fréquentiels.

Les disparités entre élocution féminine et masculine sont clairement mises en évidence : déplacement vers les hautes fréquences des noyaux vocaliques féminins, doublement du fondamental, énoncé moins énergétique.

III Analyse multi-èchelle

III.1) Ondelettes orthogonales

Pour compléter cette panoplie nous avons, à partir du formalisme de l'analyse multi-échelle, élaboré un outil applicatif pour le signal de parole. Rappelons brièvement les fondements de l'analyse. A partir de fonctions élémentaires très particulières, fonction du temps par un indice b et de la fréquence par 1/a, il est possible de décomposer tout signal x(t) par le produit scalaire :

$$Ca,b=\int_{-\infty}^{+\infty} x(t).\Psi_{a,b}(t).dt$$

avec

$$\Psi a,b = \frac{1}{\sqrt{a}}.\Psi\,[(t-b)/a]$$

Si la base est orthogonale, il est possible de reconstruire le signal x(t) à partir des coefficients d'ondelettes $C_{a,b}$ par :

$$x(t) = \int_a\int_b Ca,b \,.\, \frac{1}{a^2}\psi\, a,b(t).da.db$$

Nous avons choisi dans un premier temps les ondelettes de Daubechies [5] à support compact. Dans ce cas le facteur de compression-dilation est une puissance de 2 ($a = 2^m$, $m \in [0,M]$), de même le facteur de translation peut s'écrire $b = n.2^m$.

Les systèmes de codage dans le domaine fréquentiel sont à rapprocher de cette analyse qui consiste à fractionner le spectre en un certain nombre de sous-bandes de largeur Bk *(égales ou non), chaque sous bande* indicée k est rééchantillonnée à la fréquence de Shannon, soit 2 Bk. Les signaux issus de chaque filtre peuvent être quantifiés différemment en fonction de la fréquence : quantification accrue pour le fondamental et les formants, quantification plus grossière là où l'énergie est faible.

Le principe du codage en sous-bandes consiste à filtrer le signal par un banc de filtre miroir quadrature puis à sous échantillonner les sorties. La reconstruction se fait par l'addition de chaque sous-bande interpolée grâce à un filtre identique à celui de la bande d'analyse.

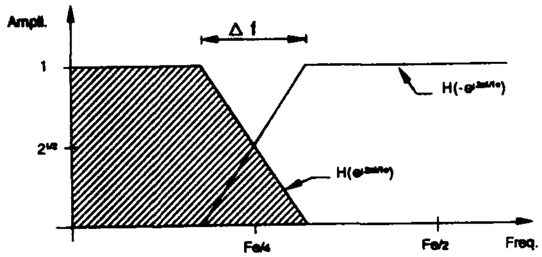

Figure 7 bis Filtrage demi-bande.

Cette technique a d'abord été implantée à partir de filtres disjoints contigus à réponse impulsionnelle finie. Elle a été ensuite étendue par l'emploi des filtres miroirs en quadrature, permettant une reconstruction quasi parfaite du signal. Le filtre demi-bande, tel qu'il est décrit figure 7 est classiquement un filtre linéaire dont la fonction de transfert vaut 1/2 à fe/4 et est antisymétrique par rapport à ce point.

Les coefficients h_n sont nuls pour n pair sauf h_0. Le gabarit est défini par l'ondulation en bandes passante et coupée et par Δf qui représente la largeur de la bande de transition. Le nombre de coefficients du filtre requit en fonction du gabarit désiré est donné par :

$$N \approx \frac{2}{3} \log \left(\frac{1}{10.\delta^2}\right) . \frac{fe}{\Delta f}$$

où $\delta = \delta_1 = \delta_2$ représente l'ondulation.

Le signal de parole étant correctement échantillonné, la distance unité sera prise égale au pas d'échantillonnage. Si S_0 est le signal d'entrée, les conditions sur l'analyse par ondelettes orthogonales discrétes [6] montrent que tous les S_j (pour j<0) peuvent être obtenus à partir de S_0. Pour tout signal f(x), l'ensemble des échantillons

$$S_j = \left[\sqrt{2^j} . \langle f, \phi_n^j \rangle \right]_{n \in Z}$$

est appelé approximation discrète de f(x) à la résolution 2^j. Cette approximation discrète caractérise complètement l'approximation continue:

$$\langle f, \phi_n^j \rangle = \int_{-\infty}^{+\infty} f(x) . \phi_n^j (x)\, dx$$

$$= \int_{-\infty}^{+\infty} f(x) . \phi^j \left(x - 2^{-j} . n\right) dx$$

S_j est alors la résultante de la *convolution de f(x) par $\phi^j(-x)$ échantillonnée* à 2^j. En fait, S_j correspond à un filtrage passe-bas de f. Tous les détails plus petits que 2^j sont éliminés.

En posant :

$$h(n) = \frac{1}{\sqrt{2}} \langle \phi_o^{-1}, \phi_n^o \rangle$$

la réponse impulsionnelle d'un filtre discret H et en notant $\underline{H}$ le filtre symétrique de réponse impulsionnelle :

$$\underline{h}(n) = h(-n)$$

il vient :

$$\sqrt{2^j} \langle f, \phi_n^j \rangle = \sum_k \sqrt{2^{j+1}} . \langle f, \phi_k^{j+1} \rangle . \tilde{h}(2n-k)$$

où <f,g> désigne le produit scalaire entre fonction f et g.
L'espace Vj ainsi défini peut être complété par un espace Oj tel que :

$$V_j \oplus O_j = V_{j+1}$$

où O^j est l'espace caractéristique des détails présents à la résolution 2^{j+1} mais absents à la résolution 2^j. Par le même principe une base orthogonale peut être décrite.

La décomposition d'un signal de parole sur O^j correspond à la convolution de S^{j+1} par un filtre $\underline{G}$ en ne conservant qu'un échantillon sur 2; G est défini par :

$$G(\omega) = e^{-j\omega}\, \overline{H(\omega + \pi)}$$

soit encore,

$$g(n) = (-1)^{1-n} . h(1-n)$$

G est le filtre *miroir de H : c'est un* filtre passe-haut défini par une réponse impulsionnelle de type "ondelette". H et G sont alors dits miroirs en quadrature et la complétude est assurée.

La structure de décomposition du signal échantillonné à 10 KHz est la même que pour l'analyse temps-fréquence. L'analyse multi-résolution est faite sur des trames de 256 points toutes les 12,8 mS. La dilatation en 2^p est effectuée, non pas en dilatant les ondelettes d'analyse, mais en sous échantillonnant d'un facteur 2^p le signal à analyser.

La projection sur une base orthogonale n'induit pas de perte ou de redondance d'informations. Pour une régularité n de fonction analysante, le support du filtre comporte 2n valeurs. Ce nombre implique que la convolution s'opère dans le domaine temporel pour des valeurs inférieures à 30. La figure 8 donne la décomposition arborescente d'une tranche de N points décomposée sur 2 niveaux; l'opération peut être renouvelée autant de fois que nécessaire (jusqu'à $\log_2 N$).

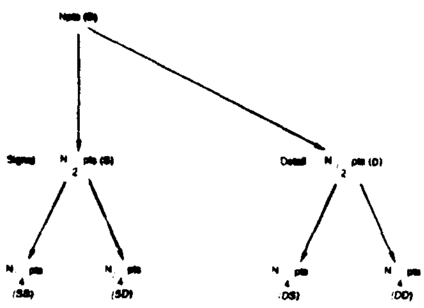

Figure 8 : Décomposition arborescente orthogonale

A titre d'exemple, nous montrons figure 9 un exemple de représentation issue d'une décomposition arborescente où les coefficients d'ondelettes ont été réorganisés en fonction de leur rang de filtrage fréquentiel. Le niveau de décomposition est fixé à 6 pour tous les canaux ce qui permet de réagencer l'analyse temps-échelle en temps-fréquence pour une meilleure interprétation. Rappelons que par convention nous parlons de "coefficients d'ondelettes" là où chaque valeur représente le résultat du produit scalaire associé aux paramètres a et b.

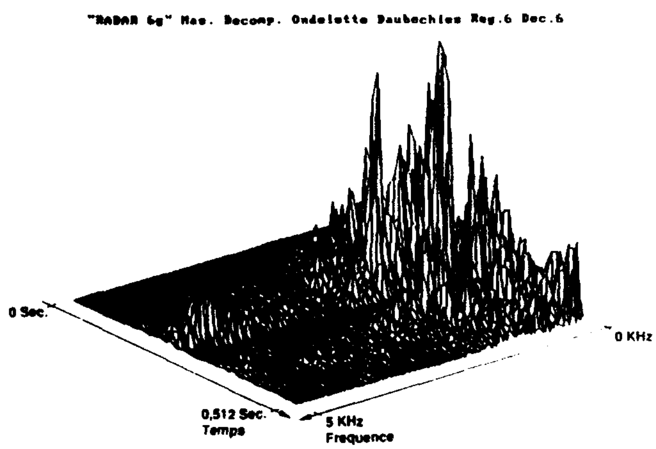

Figure 9 Analyse Temps-Echelle Réorganisée (Rég. 6, Dec. 6).

Nous montrons également à titre comparatif figure 10, un tracé similaire à la figure 9 où la régularité est fixée à 1 (fonctions de Haar). Il apparait clairement la mauvaise réjection fréquentielle de la batterie de filtres. Augmenter la régularité de la fonction, consiste à tendre vers une base "sinusoïdes amorties" dont les secondaires se situent aux alentours de -30dB (Rég. 6). Sans effort d'interprétation particulier nous pouvons cependant noter que les traits pertinents (pitch, formants, sifflante) sont bien mis en évidence par les outils proposés.

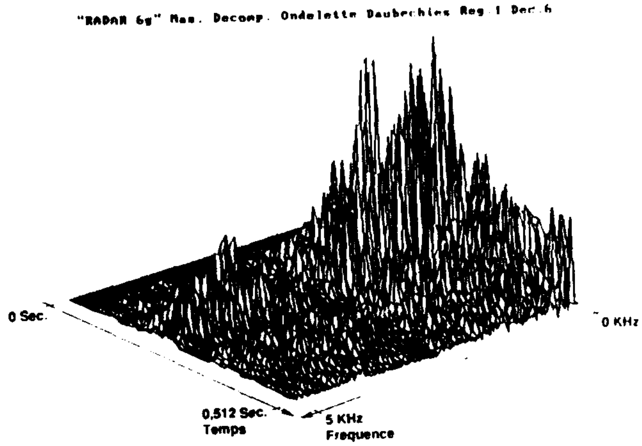

Figure 10 : Analyse Temps-Echelle Réorganisée (Rég. 1, Dec. 6)

III 2) Ondelettes continues

Une "ondelette" sera d'autant plus sensible aux transitions qu'elle possèdera de nombreuses oscillations. Il est possible d'imposer une condition d'oscillation très forte qui est la nullité des moments jusqu'à l'ordre m.

$$\int \Psi(t)\, t^k\, dt = 0 \qquad 0 \leq k \leq m$$

L'admissibilité constitue les conditions minimales pour qu'une fonction ψ soit considérée comme une ondelette : ψ doit être de moyenne nulle, et le produit scalaire doit conserver la norme. Ces deux propriétés sont contenues dans :

$$\begin{cases} \Psi \in L_2\,(R) \\ \int (|\Psi\,(\omega)|^2 (\omega) d\omega < \infty \end{cases}$$

Le critère d'admissibilité garantit la nullité des moments à l'ordre 1. Nous proposons une fonction analysante de type dérivée trois ème de Gaussienne dont le formalisme reste réel et qui grâce à une fonction de transfert asymétrique permet une bonne représentation fréquentielle; il vient

$$f'''(x) = \left[-\frac{(x-m)}{\sigma^2}\left(\frac{(x-m)^2}{\sigma^4} - \frac{1}{\sigma^2}\right) + \frac{2(x-m)}{\sigma^4} \right] \alpha e^{\frac{-(x-m)^2}{2\sigma^2}}$$

Le formalisme évoqué sous-entend que les fonctions continues peuvent être largement approximées par un facteur de sur-échantillonnage de 8. A partir de l'expression de la transformée en ondelette continue, il est possible de donner à a et b une suite de valeurs régulièrement espacées. Au terme des évaluations (détection de pitch) ce formalisme est à rapprocher du filtrage adapté (convolution par la réplique). Sans élaboration supplémentaire pour l'instant sur ce point, notre réflexion fera bien sûr partie de travaux ultérieurs.

IV Analyse Statistique Multidimensionnelle.

Pour pouvoir appliquer le formalisme de l'analyse statistique multidimensionnelle, il faut opérer une transformation des données de manière à disposer d'un tableau (paramètres quantitatifs . réalisations). A partir des canaux équi-espacés en sortie de FFT nous réalisons 16 combinaisons suivant l'échelle de Bark visualisée figure 11. Nous avons représenté également la position des divers noyaux vocaliques des 3 classes de la langue Française.

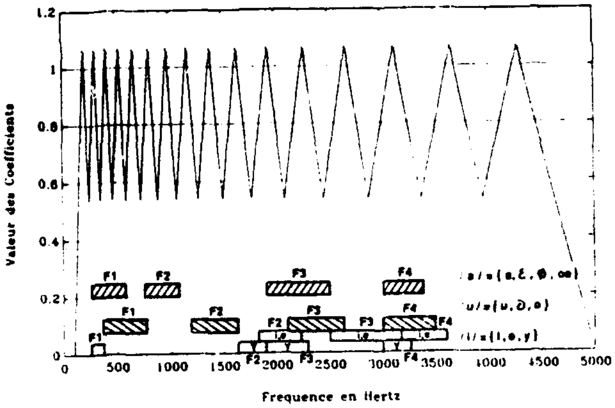

Figure 11 Fenêtrage de Bark

Nous traçons figure 12 l'allure de la répartition temporelle des 16 coefficients de Bark (discrétisés en amplitude par trame de gris). L'interprétation devient plus délicate du fait de la non linéarité des traitements, la concentration de l'énergie reste bien localisée. A partir de ces indices nous formons pour toute élocution, une matrice des corrélations (analyse normée). Après diagonalisation et réagencement des valeurs propres par ordre décroissant nous projetons le nuage à N (16) variables sur le plan défini par deux vecteurs propres (généralement le 2 et 3ième). La variance est considérée comme la dispersion de l'ensemble des trames temporelles et l'axe 1 est celui pour lequel cette dispersion est maximale, l'axe 2 possédant la même propriété sous contrainte d'orthogonalité au précédent et ainsi de suite.

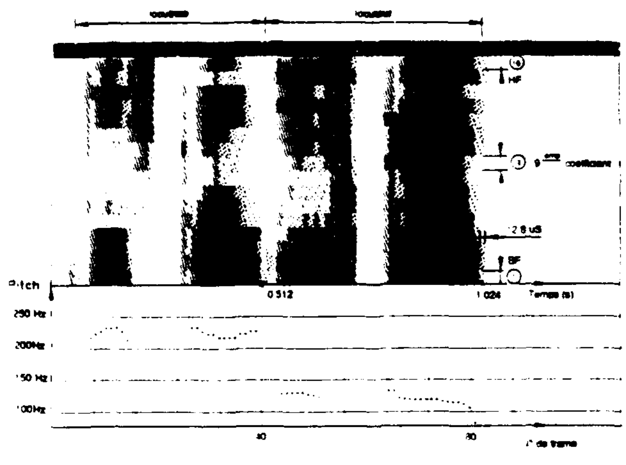
Figure 12 : Tracé temporel des coefficients de Bark

Avant d'interpréter les positions relatives de deux variables, il est necessaire de s'assurer qu'elles sont bien représentées et que la proximité de leur projection correspond à une proximité réelle. Nous avons pris le cosinus carré de l'angle reliant le plan à la perpendiculaire passant par la variable pour indicer cette qualité.

Nous avons choisi une représentation simultanée des paramètres spectraux et des trames temporelles afin de mieux cerner les éléments de comparaison entre les variables. La figure 13 représente un exemple de projections simultanées pour l'élocution "Display" déjà évoquée.

Il est à noter que les vecteurs propres sont orthogonaux mais ne sont que des combinaisons linéaires des variables d'entrée. De ce fait, la projection des trames sur le plan choisi doit être interprété uniquement intra-élocution. La mise en correspondance de 2 projections issues de 2 diagonalisations différentes, n'a pas de sens physique puisque les vecteurs définissant le plan ne sont pas issus des mêmes combinaisons.

Néanmoins, il est toutefois possible d'interpréter certains critères en se confinant à une projection. Par exemple, on peut noter une séparation très nette sur le plan (2,3) entre les 4 classes du fenêtrage de Bark (canaux BF de 1 à 4, et canaux HF 14 à 16).La trace acoustique montre clairement une séparation en 2 demi plan correspondant à la transition entre les deux syllabes du mot "Display".

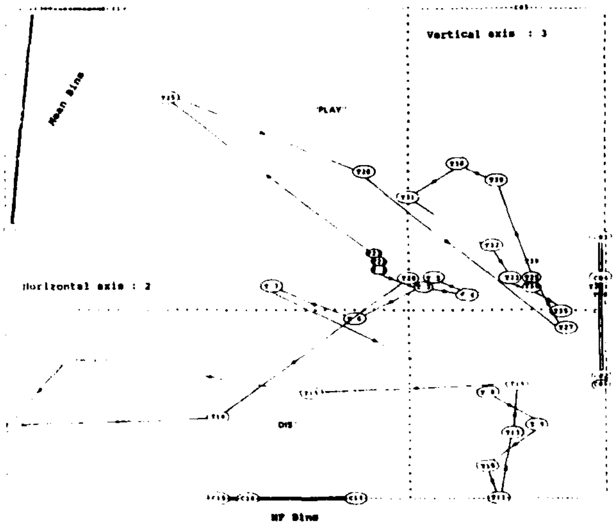

Figure 13 : Représentation simultanée sur les vecteurs propres.

Rappelons que 12,8mS sépare deux trames consécutives. La sifflante "s" est localisée de la trame T15 à T19, à proximité des canaux HF. La structure formantique du "ay" est visible à partir de la trame T21 jusqu'à T35 et est beaucoup plus proche des canaux BF. Globalement le facteur 2 représente l'axe BF à droite et non-BF à gauche (analogue à un axe fréquentiel non linéaire) , le vecteur propre indicé 3 représentant la HF dans sa partie négative.

En fait nous avons constaté que seules trois projections paraissent généralement intéressantes : il s'agit des 3 premiers vecteurs propres.

Nous avons essayé tout au long de cette définition des outils, de définir les limitations de chaque traitement proposé. La mise en évidence du compromis localisation temporelle-résolution fréquentielle nous a permis de recencer la spécificité des algorithmes proposés.

V Prise de son

Les limitations inhérentes à la prise de son sur avion d'armes sont dues essentiellemnt aux résonances du masque inhalateur et du circuit de gaz (clapets, surpression). L'inspiration, largement HF, pénalise la détection de fricatives.

A ce stade de la réflexion, il faut avoir à l'esprit l'impérieuse nécessité de conserver tout au long de la phase de reconnaissance, un recueil acoustique aussi proche que possible des références acquises au sol. Toute disparité dans cette prise d'information qui éloignera les vecteurs d'acquisition des vecteurs cibles, telle qu'une fuite du mélange gazeux, un mauvais positionnement ou un déplacement du masque sous accélération, le type ou la position du microphone pénalisera d'autant le taux de reconnaissance.

VI Incidence du facteur de charge sur la production de parole

La méthodologie adoptée pour l'étude des retentissements du facteur de charge a consisté :

- dans un premier temps, à bâtir et réaliser une expérimentation préliminaire en centrifugeuse afin de tester les paramètres dimensionnants de l'élocution sous accélération. Les structures phonétiques simples : voyelles, syllabes, mots ont constitué les entités minimales. Plusieurs mots (dissyllabes lexématiques ou non) et des phrases complétes, grammaticalement correctes, faisaient également partie du panel et permettait de tester les éventuelles modifications prosodiques. La connotation opérationnelle résidait dans l'utilisation d'une dizaine de mots à caractère fonctionnel. Les sujets étaient au nombre de 6 (5 hommes et une femme).

- dans un deuxième temps, en l'élaboratoin d'une syntaxe à 42 mots dont l'évaluation, en terme de taux de reconnaissance, a été menée à 1,4G, 3G et 6G. La longueur des phrases était de 8 mots maximun, le facteur de branchement moyen de l'arborescence était de 8. Cinq locuteurs masculin et la même locutrice que précédemment constituaient le panel d'évaluation.

VI 1) Eléments physiologiques

Nous avons procédé après la majorité des lancements à un examen ORL des voies aériennes supérieures : examen des fosses nasales et des sites anatomiques mobiles. L'objectif de ces examens était d'apprécier la coloration des muqueuses, avec sous jacente l'hypothèse que les efforts vocaux sous facteur de charge entrainent une congestion (rubéfaction) des muqueuses qui tapissent les organes mobiles. Un examen au miroir laryngé a été pratiqué avant et après lancement.

Nous donnons tableau 2 les résultats des quotations colorimétriques pour tous les sujets. Les trois niveaux d'appréciation (o : pas de changement, + : léger changement, ++ : très net changement) vont du rose au très rouge.

SUJET	PIECES FIXES	PIECES MOBILES
1♀	o	o
2♂	+	++
3♂	+	o
4♂	++	+
5♂	o	++
6♂	+	+

Tableau 2 : Modifications congestives des muqueuses

Dans la mesure où le larynx n'est lié à aucun os et se trouve tenu par une série de muscles, il aura tendance, sous accélération, à descendre (notamment pour les voyelles postérieures). D'autre part, le basculement mécanique du cartilage thyroïde sur le cartilage cricoïde aura pour effet d'accroître la tension des cordes vocales ce qui produira une augmentation de la fréquence fondamentale.

Enfin, en ce qui concerne les cordes ocales deux hypothèses plus délicates à vérifier peuvent être émises : d'une part, le fait que l'accélération s'effectue dans un sens qui s'oppose à l'écoulement de l'air pourrait modifier la forme glottique; d'autre part, le temps nécessaire à l'abduction et à l'adduction des cordes vocales qui, en raison d'une mobilité limitée, devrait augmenter.

Les cavités situées au dessus du larynx constituent des résonateurs supraglottiques (cavité pharyngale, buccale et nasale). Le volume et la forme de ces cavités pourraient être réduit par les tensions exercées sur les différents muscles, les résonances auront alors tendance à se déplacer vers les hautes fréquences.

La langue est largement affectée par l'accélération. Les constrictives dentales demandant son positionnement précis sont les premières touchées.

L'ouverture de la mandibule rend difficile l'articulation des consonnes bilabiales.

VI.2) Corrélats acoustiques

La définition de modèles de variation acoustique est indispensable pour introduire des algorithmes de compensation permettant d'améliorer des scores de reconnaissance en ambiance avionique. L'analyse des changements qui interviennent doivent être suffisament reproductibles pour pouvoir dégager des axes d'invariance.

La première phase (items langagiers non opérationnel) a mis en évidence :

- une augmentation notable de la fréquence du fondamental (pouvant passer de 130Hz à 200Hz pour un locuteur, voire doubler pour la locutrice et dépasser 300 Hz). Nous donnons figure 14 un exemple caractéristique de ce phenomène pour l'élocution "Radar" à 1,4G et 6G (Sonogramme bande large).

- un renforcement notable des hautes fréquences, rehaussé par le préaccentuateur numérique,
- un accroissement du niveau énergétique, dont l'effet est inhibé par les caractéristiques de la chaine de paramétrisation,
- une variabilité accrue pour les formants les plus hauts. Cette caractéristique est émoussée par le fenêtrage de Bark (Cf figure 12).

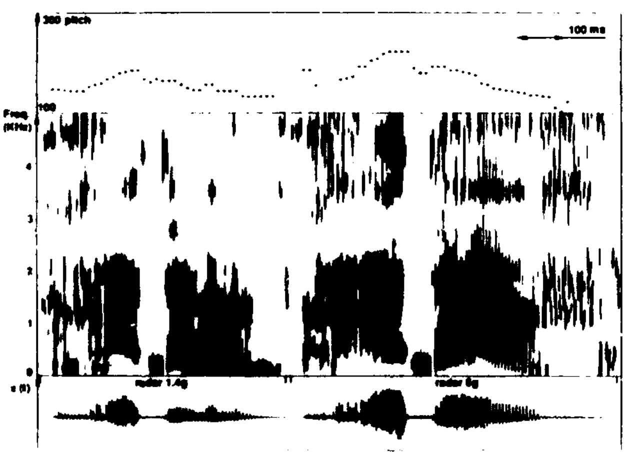

Figure 14 : Variabilité de l'élocution "Radar" sous facteur de charge

La variabilité des structures formantiques s'explique assez simplement par un raisonnement d'acoustique mécanique. La figure 15 visualise les différentes positions des formants F1 à F4 en fonction d'une constriction de 1cm/0,5 cm2. En relation avec le déplacement de l'occlusion par rapport à l'extrémité gauche du tube (simulant les lèvres) les déplacements des formants peuvent apparaitre similaires ou au contraire antinomiques.

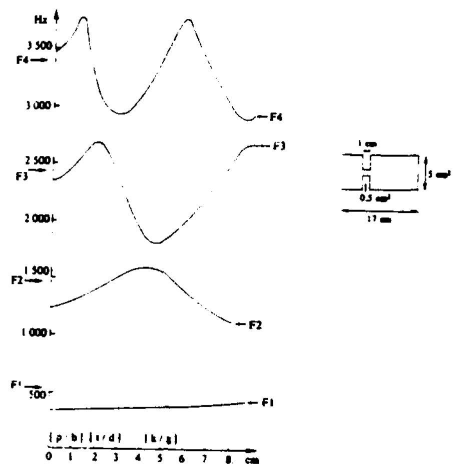

Figure 15 Resonance acoustique d'une occlusion d'après [7]

En considérant l'accélération comme un facteur qui vient se surimposer et qui a tendance à réduire les volumes (déplacement de l'occlusion vers la droite), il est alors possible d'obtenir sur un cas d'occlusive dentale (t/d) une augmentation de F2 corrélativement à une diminution de F3; de même sur une occlusive compacte (k/g) le phénomène inverse. Ces phénomènes assimilables à des battements induisent une versatilité accrue, liée au facteur de charge, pour F3 et F4.

Nous avons également constaté que le mouvement ventilatoire est corrélé de manière étroite à l'expérience du sujet vis à vis des accélérations spécifiques de la centrifugeuse et du dialogue vocal. Il peut être générateur d'expirations néfastes (au beau milieu d'une phrase) lorsque le locuteur ne maitrise suffisamment pas son rythme prosodique. Un apprentissage préalable (clear speech) améliore sensiblement ce débit d'élocution en particulier, et le taux de reconnaissance à terme.

VII Incidence du facteur de charge sur un système de reconnaissance de parole

VII 1) Campagne d'essais proprement dite

Elle s'est déroulée en mai et juin 1991. Le panel représentatif des sujets était constitué de 5 locuteurs et d'une locutrice équipés d'un masque Ulmer 87 (micro Silec S 4045) avec casque, régulateur d'oxygène et pantalon anti-G fonctionnel. Tous appartiennent au personnel du CEV.

Le chronogramme d'une scéance journalière est fournie figure 16.

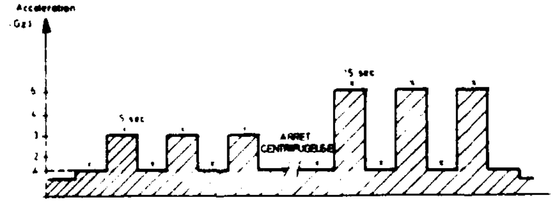

Figure 16 : Profil accélérométrique journalier.

L'apprentissage nécessaire pour la méthode de reconnaissance envisagée se déroulait systématiquement en une fois, et en prémice à tout lancement. La centrifugeuse étant à l'arrêt deux listes sont énoncées : celle des mots isolés, puis celle des mots enchainés.

La liste servant de support à l'évaluation du système de reconnaissance était constitué par une série de 100 phrases scindées en 14 listes de 30 secondes . A raison de 6 paliers journaliers à 1,4G, 3 à 3G et 3 à 6G, la totalité des listes (séquence randomisée) requiert 4 jours par individu. L'analyse du signal s'opérait de manière concomitante, un suivi médical permettait de cerner les retentissements physiologiques.

Les phrases à prononcer s'affichaient sur un écran placé dans la centrifugeuse; l'énoncé n'était donc pas spontané.

Pour une exploitation plus fine des résultats nous avons scindé les plateaux à 1,4G entrecoupés des plateaux à 3G et ceux entrecoupés des plateaux à 6G. Nous avons donc in fine, 4 conditions accélérométriques comportant chacune 100 élocutions.

Nous dressons pour chaque cas un taux de reconnaissance avec :

- une paramétrisation cepstrale sur une échelle de Bark,

- une méthode de comparaison dynamique (DTW : Dynamic Time Warping),

- une ou plusieures références par mots,

- une segmentation manuelle ou automatique, des items à reconnaitre,

- les références propres au locuteur.

A partir des premiers résultats nous avons pu constater que le taux de reconnaissance obtenu avec une segmentation manuelle était pratiquement indépendant du facteur de charge pour la syntaxe de 42 mots envisagée (Cf. figure 17).

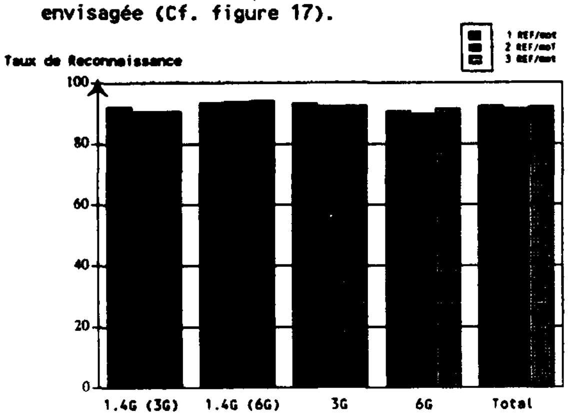

Figure 17 : Taux de reconnaissance sur 100 élocutions
(5 locuteurs, seg. manuelle).

VII 2) Durcissement de l'algorithmie

Ce durcissement tel que nous l'avons initialement prévu peut être découpé en quatre phases distinctes :

- une paramétrisation cepstrale à partir de 12 coefficients autorégressifs (LPC : linear predictive coding) venant suppléer la paramétrisation classique sur les structures voisées,

- une détection de parole robuste au facteur de charge permettant de relaxer les contraintes classiques dûes aux positions temporelles de l'alternat, souvent très approximatives.

- un filtrage numérique amont utilisé pour compenser les disparités de la répartition énergétique sous accélération,

- un assouplissement de la syntaxe prennant en compte des pauses optionnelles et des références de respiration.

VII 2 1) Codage prédictif

Nous avons choisi l'algorithme de Durbin-Levinson par bloc, ceci afin de faciliter la convergence et la stabilité des coefficients.

Si l'on suppose la linéarité du sytème de parole lors de l'émission des structures voisées, celles-ci peuvent être modélisées par un filtrage linéaire autorégressif (AR). Le nombre de poles du modèle correspond physiquement au nombre de résonateurs mis en cascade.

Nous avons voulu :

- évaluer l'apport d'un calcul de distance entre les cepstres bâtis, soit sur une analyse fréquentielle classique, soit sur une estimation autorégressive du signal de parole,

- calculer des paramètres de concordance pour un algorithme de vraisemblance acoustique de la phrase reconnue,

- fournir au besoin les coefficients d'un filtre débruiteur par réjection transverse adaptative.

L'algorithme de Durbin-Levinson résoud de manière récursive les équations de Yule-Walker synthétisées par :

$$R.a = P$$

où R est la matrice des corrélations , a le vecteur des coefficients autorégréssifs ($a_0=1$) et P est le vecteur nul, sauf pour la première composante qui est égale à la puissance de bruit. L'erreur décroit continuement lorsque l'ordre augmente.

Nous calculons tous les 12,8ms 12 coefficients (modèle à 6 résonateurs) sur un bloc de 25,6ms. Nous donnons figure 18 un exemple de densité de puissance AR d'un "O" préaccentué.

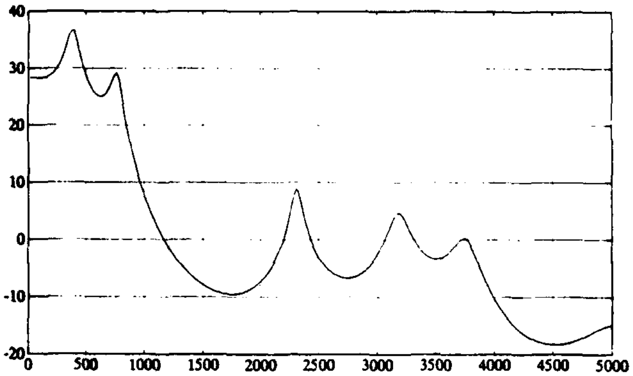

Figure 18 : Modélisation autorégressive d'un "O" (12 coefficients).

La majorité des erreurs résidant dans la reconnaisance de digits, nous établissons des élements comparatifs entre cepstres classiques et cepstres LPC pour les 10 premiers chiffres de la langue Française en laboratoire :

	Cepstres Amadeus Flottant		Cepstres LPC Levinson	
Résultats globaux item "1" à "9"	64/88	73 %	63/88	72 %
sans item "4", "8", "9"	47/60	78 %	49/60	82 %
item "4", "8", "9"	17/28	61 %	14/28	50 %

Tableau 3 : Résultats de la reconnaissance

Les résultats étant sensiblement comparables entre les deux techniques, il nous a paru inopportun de substituer la paramétrisation cepstrale par une paramétrisation LPC. La necessité d'harmoniser les coefficients pour les intégrer dans le calcul de la distance entre reférences et trame courante induit une refonte de la chaine de paramétrisation que nous prévoyons à moyen terme. Cette refonte doit fusionner des techniques anciennes (analyse temps-fréquence) et des techniques émergentes (analyse temps-échelle).

VII 2 2) Détection d'activité

L'utilisation de la commande vocale en avions d'armes est régit par l'utilisation d'un alternat qui vient indiquer au système la demande de la fonction reconnaissance. Cet alternat temporellement approximatif est du ressort de l'utilisateur et donc très versatile. Il est soumis à l'apprentissage au facteur de charge, aux ambiances de stress qui lui sont liés et au degré de motivation du pilote vis à vis de la commande vocale.

A partir de cette première localisation temporelle et conformément aux résultats de la figure 17, indiquant la constance des performances de reconnaissance lorsque les items sont segmentés à la main, nous avons contruit une algorithmie de recherche de l'énoncé.

Après de multiples architectures envisagées, notre conviction s'est forgée autour d'une détection locale autour du mot à partir de l'indication grossière de l'alternat. Le synoptique final peut être résumé figure 19 :

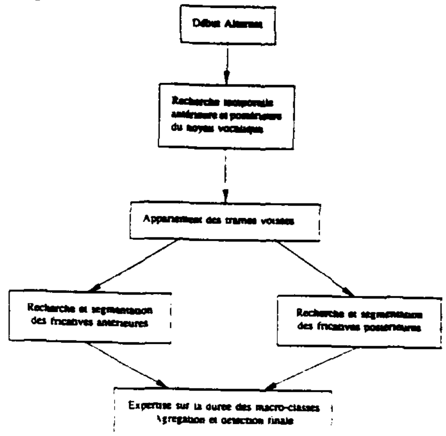

Figure 19 : Détection de parole

A partir de ce canevas général, chacune des macro-fonctions peut être établies par une multitude de méthodes qui recèlent toutes des spécificités.

VII 2 3) Détection de voisement

L'ossature de notre méthode est articulée autour une localisation efficace et robuste du noyau vocalique. Nous avons pour ce faire retenu deux principes :

-une méthode basée sur la fonction de corrélation où l'on calcule :

$$C(k) = \sum_{n=1}^{N-1-k} x(n) \cdot x(n+k) \ , \ k = 0, 1, \dots K$$

- une méthode utilisant les différences moyennes de la corrélation (AMDF : Average Magnitude Difference Function) où l'on évalue l'expression :

$$D(k) = \sum_{n=1}^{N-1-k} | x(n) - x(n+k) | \ , \ k = 0, 1, \dots K$$

Les figures 20a et 20b caractérisent les résultats obtenus.

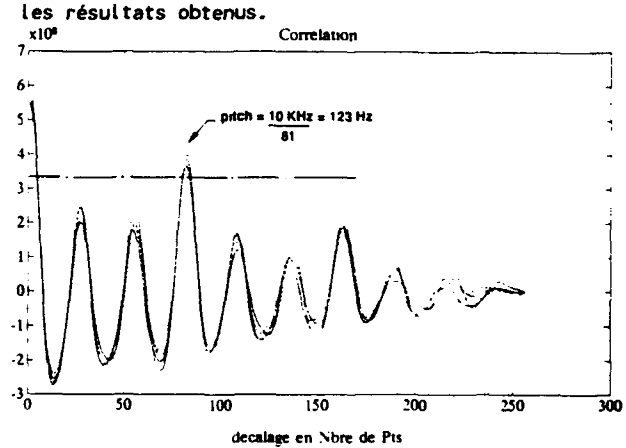

Figure 20 a) Corrélation d'un "O". (6 Trames voisées)

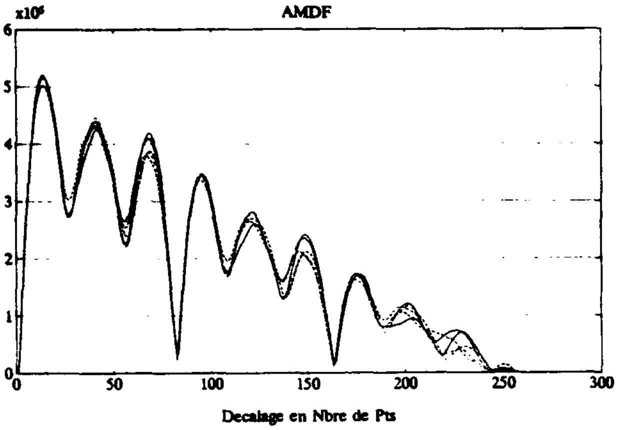

Figure 20 b) AMDF d'un "O"
(6 Trames voisées)

Alors que le maximum de la corrélation est bien localisé et facilement détectable, l'AMDF (précise sur la position de ces minimuns) requiert une expertise supplémentaire pour traiter l'aspect physique (élimination des minimuns locaux). D'autre part, une information d'énergie mutuelle a disparu par différence : le traitement du minimun absolu est en fait moins facilement exploitable.

La détection de voisement proposée peut être schématisée figure 21.

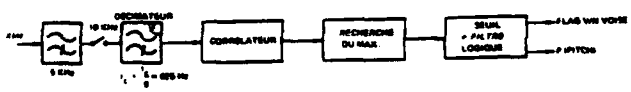

Figure 21 Détection de voisement.

L'interpolation pour estimer précisement le maximun n'est pas nécessaire à condition de garder un débit constant en sortie de décimation.

Le filtre logique élimine les trames voisées isolées et opère une agrégation des divers noyaux vocaliques. Cette expertise est fonction de l'antériorité du message .

Le dispositif de détection finale intègre après localisation du voisement une detection de fricative par filtrage fréquentiel et seuillage énergétique.

VII 4) Filtrage amont

Afin de corriger les disparités physiologiques dûes au facteur de charge nous avons placé en tête de la chaine de parametrisation 4 types de filtrage :

- F1 : filtre préaccentuateur non récursif du premier ordre (b1=-0.95).
- F2 : filtre non récursif du deuxième ordre (b1=-1, b2=0.5).
- F3 : filtre récursif atténuateur du deuxième ordre (a1=-0,7325,a2=-0,2325).
- F4 : filtre récursif atténuateur du deuxième ordre (a1=-1, a2=0,5).

Les scores obtenus sont résumés dans le tableau 4

	1.4 g (3 g)	1.4 g (6 g)	3 g	6 g
F1/F2	94.6 %	95.4 %	95.8 %	81.2 %
F3/F4	≤ 50 %			

Tableau 4 Incidence du filtrage amont

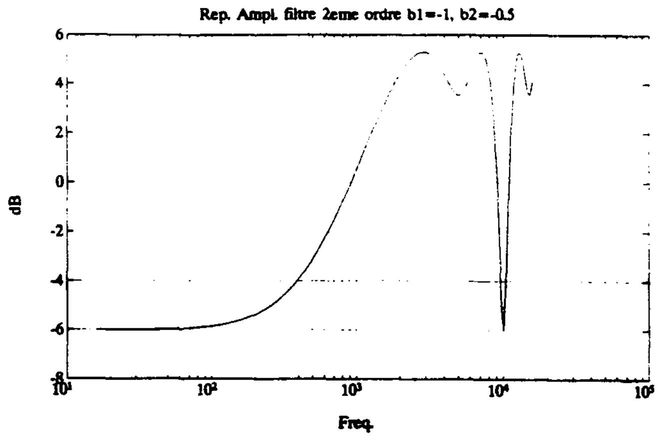

Figure 22 : Type de filtrage

Nous en déduisons l'impérieuse nécessité de préaccentuer la phase de reconnaissance.

VIII Assouplissement de la syntaxe

Afin de compenser la variabilité d'élocution sous accélération, liée au facteur humain, nous avons bati deux syntaxes régulières (S1 et S2). S1 représente la syntaxe brute; S2 référence la syntaxe modifiée par l'ajout de trois types de représentants :

- des références de pause,
- des références de respiration,
- une coarticulation sans pause (par exemple entre le mot de commande et les digits).

Nous donnons les résultats globaux pour le locuteur 5

Loc 5	S1 avec détection histogrammes locaux	S2 avec détection histogrammes locaux	S2 avec détection par maximum de vraisemblance	S2 avec détection manuelle
sur 400 élocutions (1,4 g, 1,4 g, 3 g, 6 g)	86.3 %	90.8 %	93.3 %	94.9 %

Tableau 5 : Résultats de la reconnaissance.

Le seul handicap de cette astuce, qui relaxe les limitations liées à la détection de parole automatique est d'augmenter sensiblement le nombre d'arcs syntaxiques et par delà le temps CPU de la phase de reconnaissance des formes (Cf. tableau 6).

		Facteur de branchement			Longueur de phrases			Entropie
		min	moy	max	min	moy	max	
Syntaxe	S1	1	7,7	22	3	7.9	8	1,89
	S2	1	11,8	24	2	7.2	8	2,71

Tableau 6 : Eléments de comparaison entre S1 et S2.

A ce stade de la réflexion, il nous parait préjudiciable de binariser une telle syntaxe au risque d'augmenter fortement le nombre de solutions potentielles. Le choix de plusieurs syntaxes réguliéres emboitées nous parait être plus approprié pour traiter, suivant les situations accélérométriques, les limitations physiologiques et les besoins opérationnels différents.

VIII Conclusion

Nous avons, à partir d'une expérimentation préliminaire, établi les effets physiologiques et les corrélats acoustiques de l'élocution sous facteur de charge. A partir des tentatives d'interprétations, nous avons souligné l'absence d'invariance des déformations et les rententissements pour un durcissement de l'algorithmie.

Sur des enregistrements "centrifugeuse" (facteur de charge seul), il est facile d'obtenir des scores comparables à une reconnaissance manuelle. Il suffit pour ce faire de disposer d'une détection de voisement et d'une expertise fiable, puis de prendre une heuristique d'une dizaine de trames avant et après le noyau vocalique. L'absence de bruit conduit à un taux de reconnaissance qui n'est pas pénalisé par ce procédé. En configuration opérationnelle, il faut étendre cette démarche par une réflexion globale, à savoir l'aspect débruitage et confirmation des trames de bruit. Le débruitage [8] ne doit pas être vu uniquement comme un facteur améliorant la reconnaissance, mais surtout comme un outil d'aide à une détection robuste, donc par voie de conséquence à un taux de reconnaissance accru.

La future étape est la validation de l'algorithmie sur une syntaxe à 155 mots (type Rafale D) en centrifugeuse. Au terme de cette phase, il sera possible de transposer l'algorithmie pour un portage sur avion banc d'essai, afin d'en évaluer les performances opérationnelles en situation réelle.

Remerciements

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A SYSTEMS APPROACH TO THE ADVANCED AIRCRAFT MAN-MACHINE INTERFACE

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CONTENTS

1. SUMMARY

Current thinking on the aircraft man-machine interface focuses primarily on the cockpit. My proposed approach will view the mission planning/mission rehearsal and the aircraft as an integral system that can perform three functions: (1) dynamically adjust itself to the particular pilot response in the planning/rehearsal stage, (2) adjust itself during the strike based upon the scenario encountered, and (3) adjust itself after each mission to enhance planning for follow-on missions. The objectives are to improve strike effectiveness and to shift portions of the pilot's work load from the attack to the planning phase of the strike.

This concept can be implemented using existing and emergent technologies. Aircraft now coming on line are equipped with removable disks that are used to load mission specific data for the avionics and weapon systems (maps, ELINT files, route plans, navigation data, target coordinates, etc.). Mission planning systems are being configured not only to provide these data, but also to evaluate post flight data from flight recorders. Mission planning and rehearsal with the resulting aircraft mission data package will provide more inputs for the aircraft mission computer that will eventually fly the mission. Inter-aircraft computer communications will support adaptively optimizing the strike based upon the threat and target conditions encountered and the success of the strike to that point in time (adaptive mission control). Pilot intervention may only be required for aircraft-to-aircraft combat, freeing the pilot to attend to weapon aimpoint selection tasks (where the automatic systems have low confidence in their selections) or for unplanned contingencies. This paper describes the mission planning/aircraft system, the notional aircraft avionics for adaptive mission control, and the implications for the man-machine interface.

2. INTRODUCTION

The future is certain--things will change. The systems developed today for service 10 years from now will enter service in a different world. The trend is toward a military half the current size--fewer aircraft, fewer carrier decks, fewer forward bases--to face enemies with weapons, including ballistic missiles, fighters, and air defenses, much more capable and mobile than currently exist. And yet the desires and expectations will be for a vastly improved capability to project force. The desires derived from Desert Storm are a good example--one target/one warhead; no fratricide; real time utilization of intelligence data; higher sortie rates for manned aircraft; joint force coordination; effective ballistic missile launcher targeting; no loss of people; minimum collateral damage; etc. How will we provide these dramatic improvements with only half the resources? A vision is forming that the dramatic improvement will come about through the tactical utilization of all our reconnaissance data and real time adaptive coordination of weapon platforms. Cooperative targeting, netted fire control, terrain reference navigation, over the horizon targeting, and sensor-to-shooter data links are becoming the buzz words. To ensure that pilot overload, as illustrated in Fig 1, is not the weak link in the chain, mission planning and the aircraft must be developed as an integral system.

In the next section, an overview of the advanced aircraft man-machine system is presented. The following sections present notional components of mission planning and aircraft subsystems. Lastly, I will summarize our development approach.

3. ADVANCED AIRCRAFT MAN-MACHINE SYSTEM

There are three goals, as illustrated in Fig 2, for this notional aircraft man-machine system: (1) improved discriminate use of force for reduced collateral damage, improved target kill, and elimination of fratricide; (2) improved effectiveness in terms of reduced timelines to achieve missions, increased platform utilization in non-traditional roles, reduction in the number of aircraft and weapons necessary to accomplish a mission, and improved survivability; and (3) reduced pilot work load to enhance mission adaptability, shorten mission response times, and increase the number of sorties a pilot is able to fly.

As witnessed in the Gulf War, daily strike plans were based on an Air Force mini-SIOP (Single Integrated Operational Plan) type of listing (Ref 1). From this integrated plan, generated for the regional commander in chief (CINC), the multi-national forces and various services developed the detailed mission plans. As pressure for response time and

effectiveness increase, and the resources available to a theater commander decrease, the function of mission planning will assume a real time adaptive nature. And direct control of aircraft for time critical targets/situations will be assumed by the theater commander, as illustrated in Fig 3. Some of the traditional mission planning functions, such as route and attack planning, will have to shift from airfields and carriers to the aircraft. Other functions such as queuing for cooperative targeting of short dwell targets, resource reallocation (tankers, combat air patrol, defense suppression, etc.), and deconfliction will be handled in real time by the CINC.

An architecture for the mission planning/aircraft system that could facilitate real time dynamic reallocation is illustrated in Fig 4. The key feature of the architecture is that mission planning and the aircraft are considered a system. And as a system, the components of each can be synergistically tailored to reduce the pilot work load while providing more capability.

The single most important feature of the system is the rapid mission assessment function: the ability to verify target kills on board the aircraft and to make use of that data. In order to husband our weapon and pilot resources we only want to kill a target once. "It was only when the Iraqis started to paint bomb holes onto undamaged HASs [hardened aircraft shelters] that the Coalition realized that it had no record of which shelters had been attacked and which were really undamaged" (Ref 2). For many targets, an unverified kill requires another mission.

Other features include the following.

• Rapid strike planning optimizes the strike, including individual routes, terminal area acquisition, and weapon release plans, given the targets and resources available.

• Contingency planning considers operations being conducted adjacent to the mission operation area.

• Mission control and rehearsal package preparation includes automated flight options for rehearsal either in ground simulators or in the cockpit.

• Navigation and precision registration for registration with other allied forces, registration with absolute earth coordinates, and registration with the target.

• Cockpit mission rehearsal, attack cueing, and assessment through multimedia display of mission rehearsal data, real time targeting sensor/data base registration, or a quick look assessment of an earlier engagement.

• Adaptive mission control for enroute reoptimization of strike resources, routes, and weapon release based upon current conditions.

• Data representation and storage, including data compression and decompression for cockpit utilization, and capture of significant mission data for later assessment.

4. MISSION PLANNING SUBSYSTEM

Mission planning must be highly automated and efficiently and effectively interfaced to the aircraft and crew. It must be developed with the pilot foremost in mind and with the assumption that all functionality will eventually end up in the aircraft. The recurring emphasis on "rapid" throughout this section of the paper is not accidental. "Timely results" must be produced for the planning systems to be used widely in combat situations. The four functions defined for this notional planning system, as mentioned above, are: (1) rapid strike planning, (2) contingency planning, (3) rapid mission assessment, and (4) mission control and rehearsal package preparation and mission rehearsal.

Rapid strike planning will start with a data base comprised of a growing number of data items, including the operational plans, maps, charts, GPS almanac, SIGINT, IMINT, etc., orders of battle, weapons characteristics, aircraft characteristics, threat lethalities, sensor characteristics, signatures, target vulnerabilities, etc. Some of these could be updated through real time inputs. The first step in doing anything "rapid" with this growing mountain of data will be automated data fusion and understanding, as illustrated in Fig 5. What things are, where they are, what they look like in selected parts of the spectrum, their vulnerabilities, lethality, and value, and anything else we want to know about them, must be automatically correlated or extracted and put in a *usable form*. The RADIUS project at Defense Advanced Research Project Agency (Ref 3) for automated object recognition, three-dimensional feature extraction, and change detection from two-dimensional and stereo pair imagery, is an excellent example of growing technical capability in this area.

The second step in rapid strike planning is to build a coordinated attack plan, allocating appropriate aircraft and weapons to appropriate targets, and providing coordination for defense suppression, jamming, tanking, etc. Products currently exist that do resource allocation and optimization, such as SCT's FLAP system (Ref 4), but optimization of complex resource allocation is computer intensive, especially if we need sensitivity analysis to show the operator what the trade-offs are. Work at the Jet Propulsion Laboratory is addressing this issue through the fabrication of specialized neural network chips specifically tailored to rapidly solve this class of problems (Ref 5).

The third step is to determine optimum aircraft routes for ingress and egress. Again, systems have existed for years to do auto-routing of cruise missiles, taking into account terrain clobber, survivability, and navigational reference locations. But these algorithms are also computationally intensive and

will require specialized chips to run real time interactive (Ref 6).

The last step that must be coupled to the route plan is to produce a viable terminal area plan that maximizes the potential to kill a target while balancing survivability and the ability to verify the kill. I would like feedback on efforts in this area, particularly efforts that consider uncertainty in registration of the aircraft to the target, aircraft kinematic limitations, weapon characteristics, sensor characteristics, target characteristics and vulnerabilities, mission assessment, and "smart search."

Contingency planning, as illustrated in Fig 6, will grow in importance as capability and demand for dynamic reallocation of aircraft increases. The mission prepared for may not be the mission flown. To enhance both the command's ability to reallocate on the fly and the success of the mission, the planning should consider operations being conducted adjacent to the mission area. Given the aircraft's configuration, weapons, etc., it is possible to evaluate suitability for contingencies that could arise and to plan for those where a capability exists.

Rapid mission assessment is the single most important aspect of mission planning. If an unverified kill requires another mission, then the approach to maximizing probability of kill and aircraft survivability is to plan for and to be able to rapidly verify that kill. Best estimates of weapon impact points, along with supporting data such as targeting sensor video, designator aimpoints, timelines verifying designator maintenance through weapon impact, etc., must be collected in the aircraft and automatically registerable with the mission planning data base, as illustrated in Fig 7.

Mission control and rehearsal package preparation and mission rehearsal are separated because of the focus on response time and dynamic allocation of aircraft. The mission planning output, listed in Fig 8, must include everything necessary for mission accomplishment and for the mission rehearsal. If the time and facilities exist for rehearsal, such as the virtual display systems being demonstrated within the military (Ref 7) and now available for multiplayer video game participants, the pilot must be permitted an avenue to modify the plan within the operational constraints.

5. AIRCRAFT SUBSYSTEM

Like mission planning, future aircraft must be highly automated and efficiently and effectively interfaced to the crew. Again, it must be developed with the pilot foremost in mind and with the assumption that all mission planning functionality will eventually end up in the aircraft. The emphasis shifts from "rapid" to real time or better. The four functions defined for this notional aircraft system, as mentioned above, are: (1) navigation and precision registration; (2) cockpit mission rehearsal, attack cueing and assessment; (3) adaptive mission control; and (4) data representation and storage.

Navigation and precision registration, as illustrated in Fig 9, is going through revolutionary change with the advent of the global positioning system (GPS). For the first time the potential exists for everyone to know where they are, in absolute earth coordinates, to a high degree of accuracy. Coordination of allied forces will be significantly enhanced as long as operations proceed as planned, or communications are adequate, and no or only intermittent jamming is encountered. However, information friend, foe, or neutral (IFFN) will still be necessary because every friendly position cannot be known in the dynamics of battle. Also registration to targets will require a GPS survey of the site, or registration with a location from which the target can be mensurated. Several target relative techniques are operational, including terrain comparison navigation (TERCOM) and digital scene matching area correlation (DSMAC). Several others are under development, including the application of differential GPS references at locations from which target coordinates can be accurately surveyed*; variations on DSMAC, utilizing FLIR or radar significant registration features that can be accurately tied to target locations**; and combinations of registration techniques tied to accurate digital terrain maps, generally referred to as terrain reference navigation (TRN) systems, which permit covert nap of the earth pilotage and weapon delivery.

Some form of both differential GPS and terrain/feature reference navigation (TRN) for target relative delivery will probably be implemented because of the compelling weapon delivery accuracy and aircraft survivability implications. And both of these systems will require large area image data bases in which target images can be registered and mensurated. TRN will additionally require references and digital maps aboard the aircraft.

Cockpit mission rehearsal, attack cueing and assessment is illustrated in Fig 10. The hallmark of targeting and mission planning in response to critical short dwell targets will be that it has to be performed primarily in the cockpit. Timelines dictate that the most expedient options to prosecute short dwell targets will be either reallocation of aircraft involved in other missions or vectoring of forward positioned CAP aircraft awaiting such an assignment. In either case the detailed mission planning cannot commence until designation of the target area. To ensure strike success in these situations, multimedia cockpit presentation will be

*Working papers of Eyring, D., Greenspan, R., Phillips, R., and Schmidt, G., "Application of Relative-GPS/Inertial Techniques to Precision Weapons Guidance", The Charles Stark Draper Laboratory Inc.

**Working papers of Sutton, A.G., Ditzler, W.R., and Robison, D.L., "NWC Targeting and Fire Control Division Sensor Fusion Programs", Naval Air Warfare Center Weapons Division, China Lake, Calif.

necessary to support rehearsal, target cueing, and attack assessment. Audio, three-dimensional terrain display, and a highlight of critical instrument displays could be used to rapidly review the mission plan, route, funnel features, timelines, etc., in a time compressed fashion under pilot control. In the terminal area, sensors could be aligned for target registration, and cues displayed to assist with target acquisition and weapon release. Following the attack, the target complex (or uncertainty area plan view) could be displayed, with best estimates of weapon impact points and probability of kill, along with supporting data such as targeting sensor video, designator aimpoints, etc.

Adaptive mission control (AMC), as illustrated in Fig 11, serves three functions: (1) reoptimizes, enroute, strike resources, routes and weapon release based upon current conditions; (2) provides expert advice on tactics; and (3) provides the option of automatic pilotage. If the mission has been preplanned, AMC will update the plan based upon the situation encountered. If the mission is a reallocation or vectored intercept, AMC will plan from current position and provide the necessary data for mission rehearsal, attack, and assessment, using the same processing techniques embedded in the ground based mission planner. In addition, the AMC could have a fuzzy logic expert system. Such systems are well suited to uncertain and probabilistic situations such as this (Ref 8). Following are examples.

- General core knowledge that is applicable to most missions
  a) If fuel is low, replan for nearest target.
  b) If there is little terrain advantage, stay high and suppress the threat.
  c) If mission variance is low, go automatic.
- Mission/strike specific knowledge (strike specific parameters)
  a) If weather ceiling is low, shift to contingency plan "N".
  b) If primary target is missing, replan to hit target "Y".

The pilot should have the option of using the AMC as an auto pilot to relieve the work load to facilitate mission rehearsal and assessment, or when automated terminal maneuver has a significantly greater probability of success (such as a calibrated weapon release off a target relative reference).

Data representation and storage, as illustrated in Fig 12, includes both the mission data base, loaded from the mission planner, and the mission record. The data necessary to support navigation and precision registration, cockpit mission rehearsal, attack cueing and assessment, and adaptive mission control are potentially beyond the capabilities of projected storage technology. Strategies for compressed data representation of "N" dimensional targeting data have been undertaken (Ref 9), and substantial commercial effort is under way in image compression to facilitate timely transmission on local area networks. But the combination of data base size, manually intensive data extraction requirements, and computational intensity of compression and decompression techniques will keep most concepts presented here from having operational utility in dynamic combat situations, unless new strategies for knowledge representation emerge.

6. STRATEGY AND DEVELOPMENT APPROACH

We are developing a strategy, summarized in Fig 13, that focuses on three aspects of the problem (see Fig 1): (1) efficient and effective crew interfacing, (2) a correlated and integrated mission data base, and (3) efficient extraction of data which supports rapid (re)targeting. We believe that by focusing on what the aircraft and crew need, how to best utilize what they need, and how to best interface with the crew to provide those needs, we can *define the minimum knowledge base* that is required. Once the knowledge base is defined, we can examine the current and planned data bases and real time data feeds, and determine how to *represent only the data we need*. In parallel, we can *address efficient extraction*--data transformation, registration, sorting and merging, and expert control.

Our development approach has been to construct a strike data and mission planning laboratory, as illustrated in Fig 14. The primary function of the laboratory is to support the development of tactical aircraft mission planning system (TAMPS) modules for aircraft and weapons. But the secondary function is to provide the facilities to examine the issues of a correlated and integrated mission data base, and to provide efficient extraction of data that supports rapid (re)targeting. Based upon our current understanding and strategy, we are teaming with Human Factors experts to address the issue of efficient and effective crew interfacing.

7. CONCLUSIONS

There is a synergistic ground swell of technical capability, and political and financial pressure, to vastly improve our ability to project force with reduced resources. A vision is forming that the vast improvement will come about through the tactical utilization of all our reconnaissance data and through real time adaptive coordination of weapon platforms. To ensure that pilot overload is not the weak link in the chain, mission planning and rehearsal and the aircraft must be developed as an integral system.

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9. ACKNOWLEDGEMENT

My sincere appreciation to Dr. Chi-Kin Lam, Danny Searle, and Wayne Tanaka for their synergistic support in developing these concepts and for their review and advice in writing this paper.

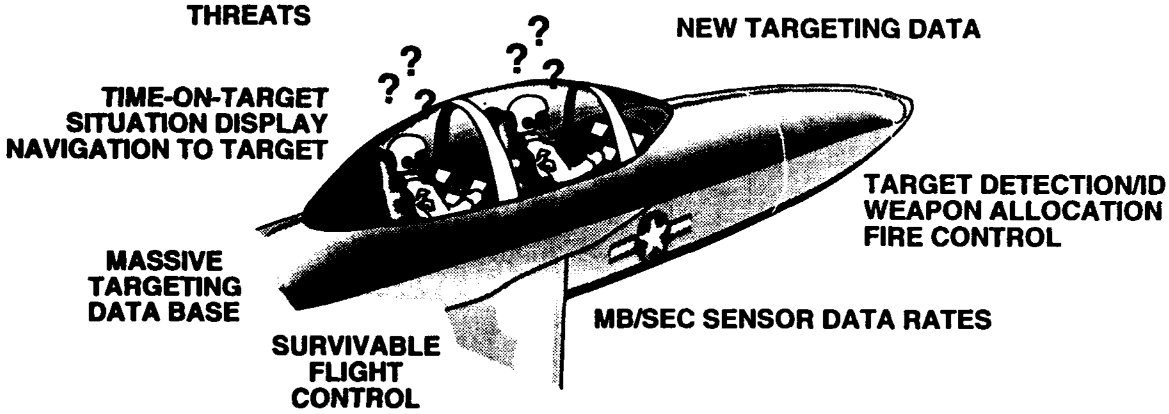

Fig 1. The Problem.

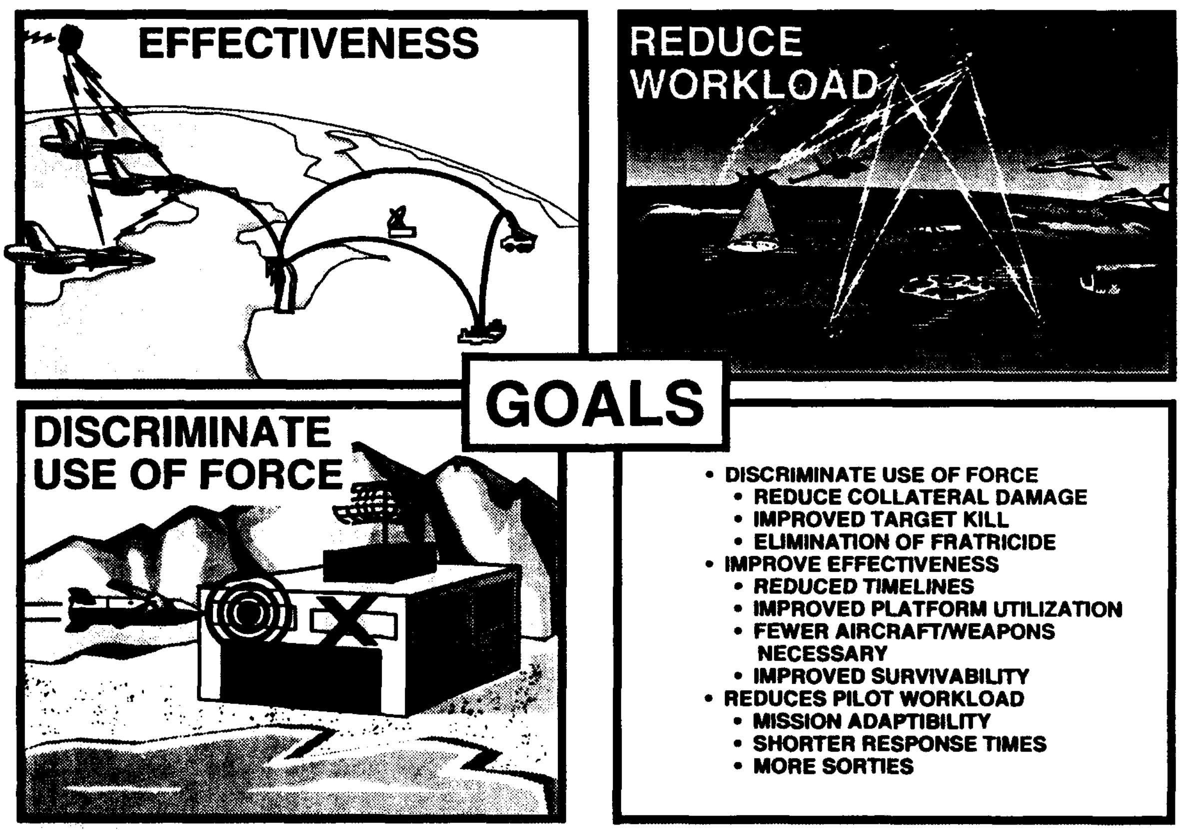

Fig 2. Goals for Advanced Aircraft Man-Machine System.

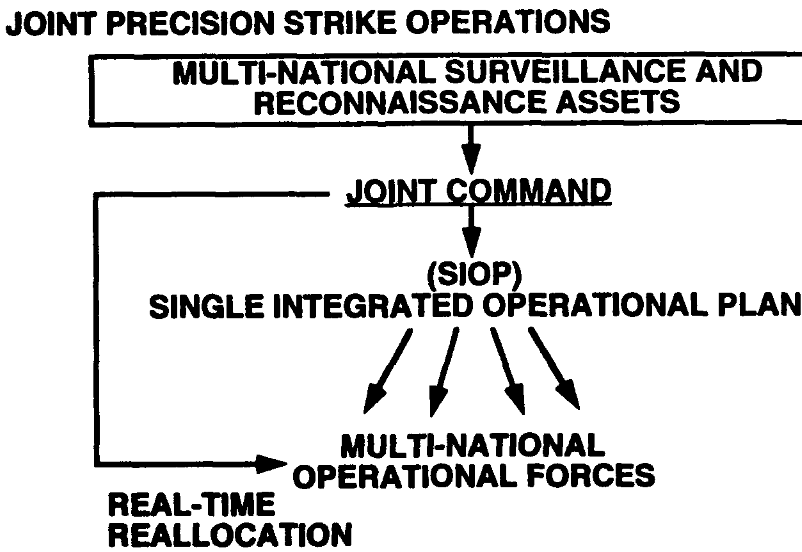

Fig 3. Joint Force Planning.

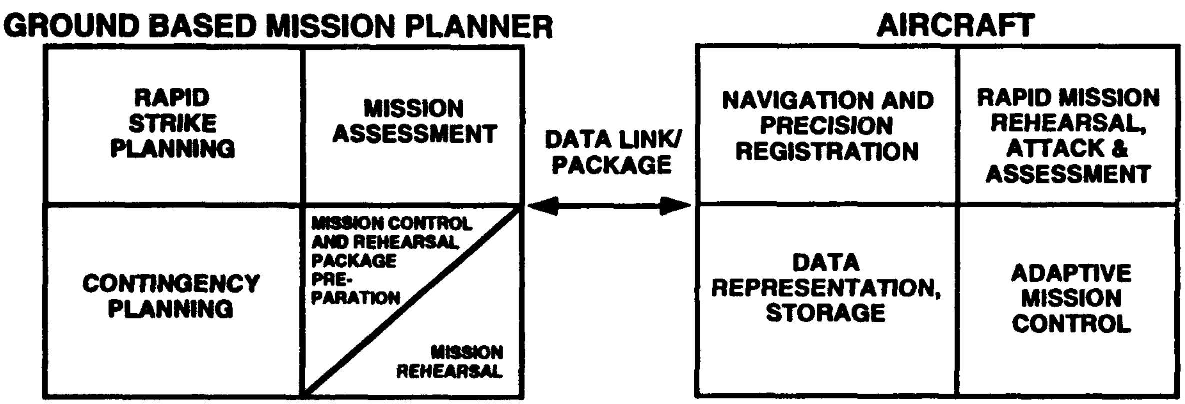

Fig 4. Advanced Aircraft Man-Machine System.

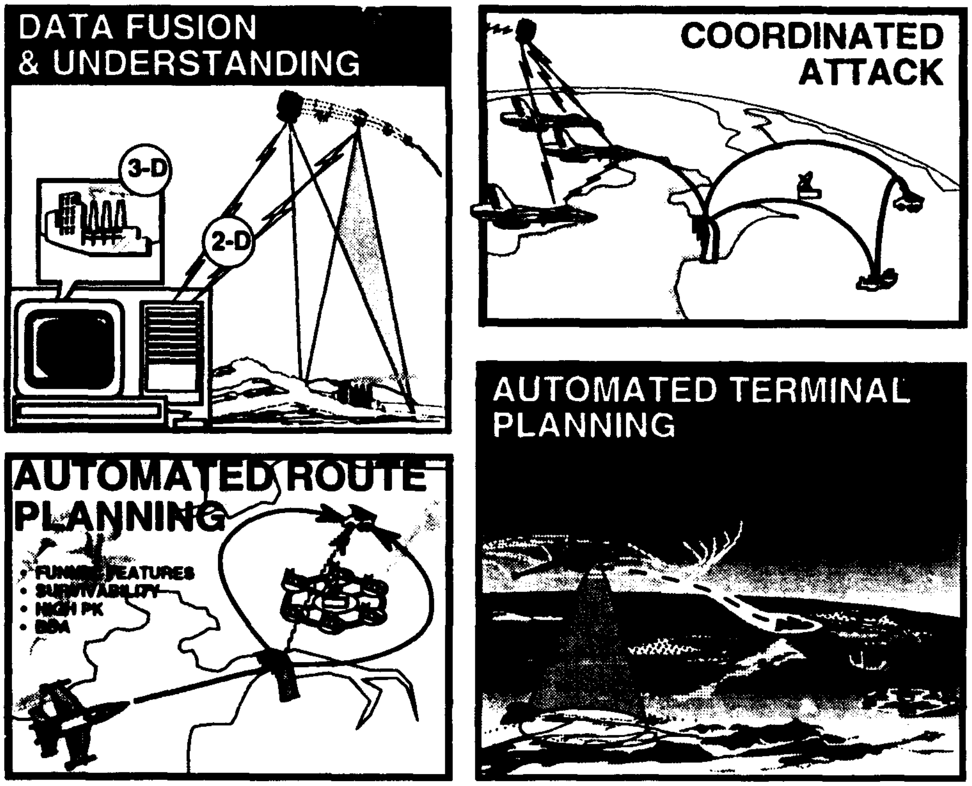

Fig 5. Rapid Strike Planning.

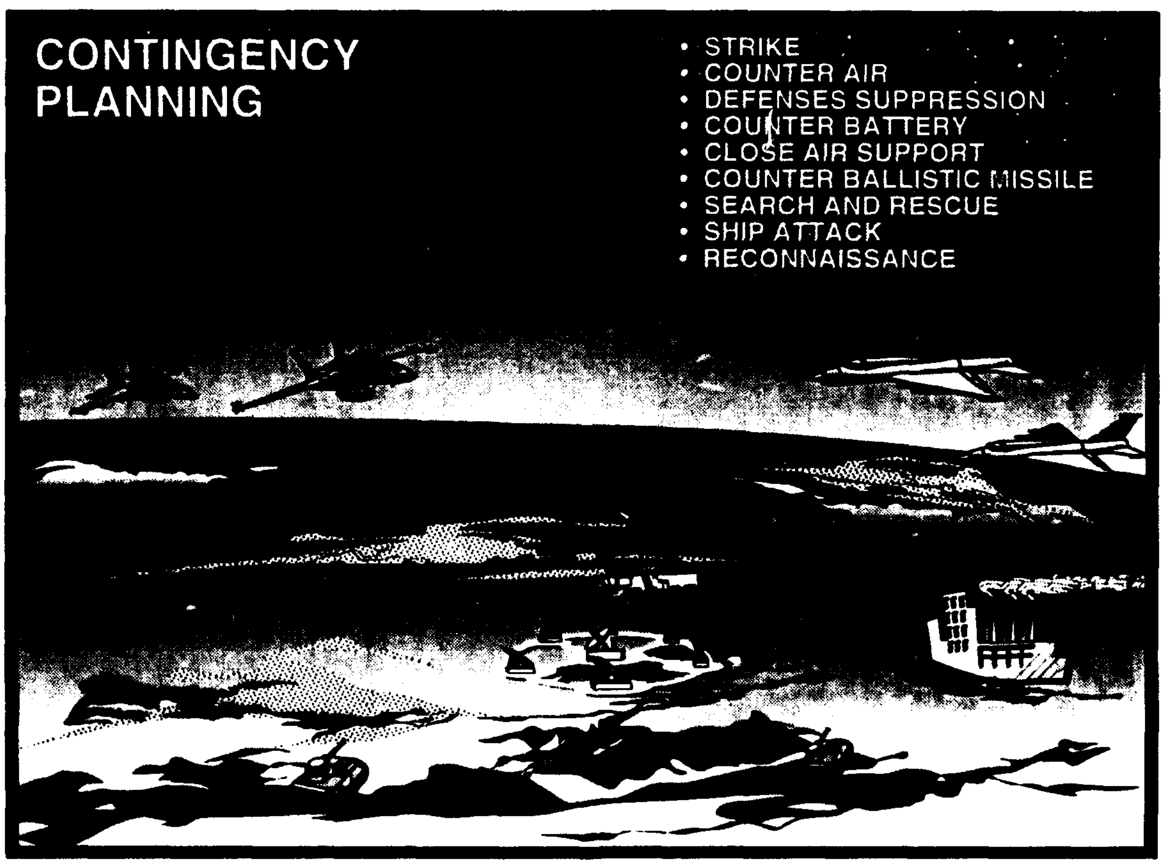

Fig 6. Contingency Planning.

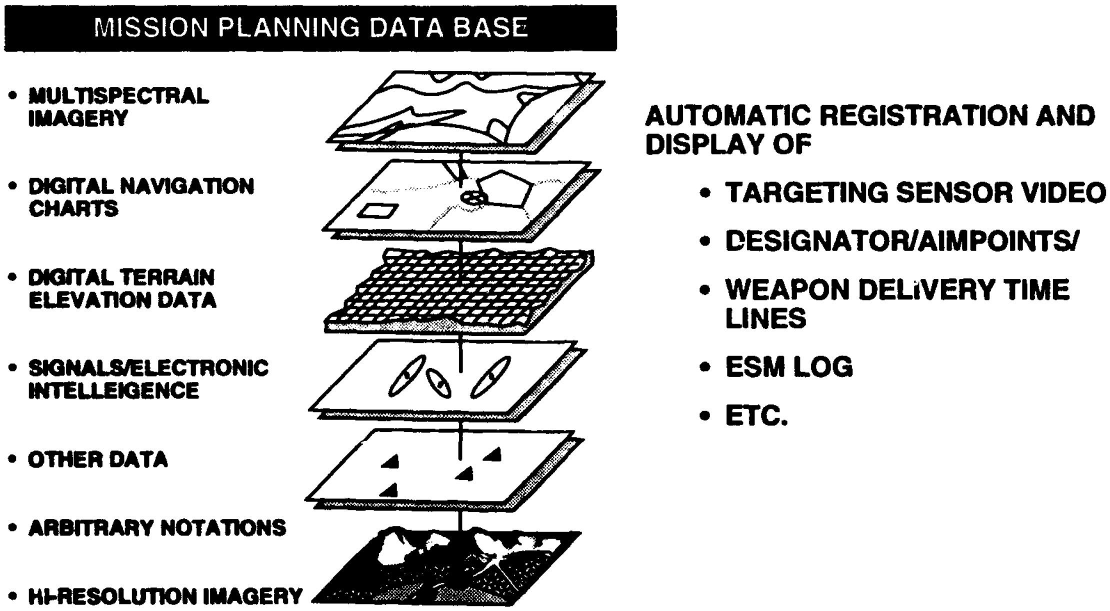

Fig 7. Rapid Mission Assessment.

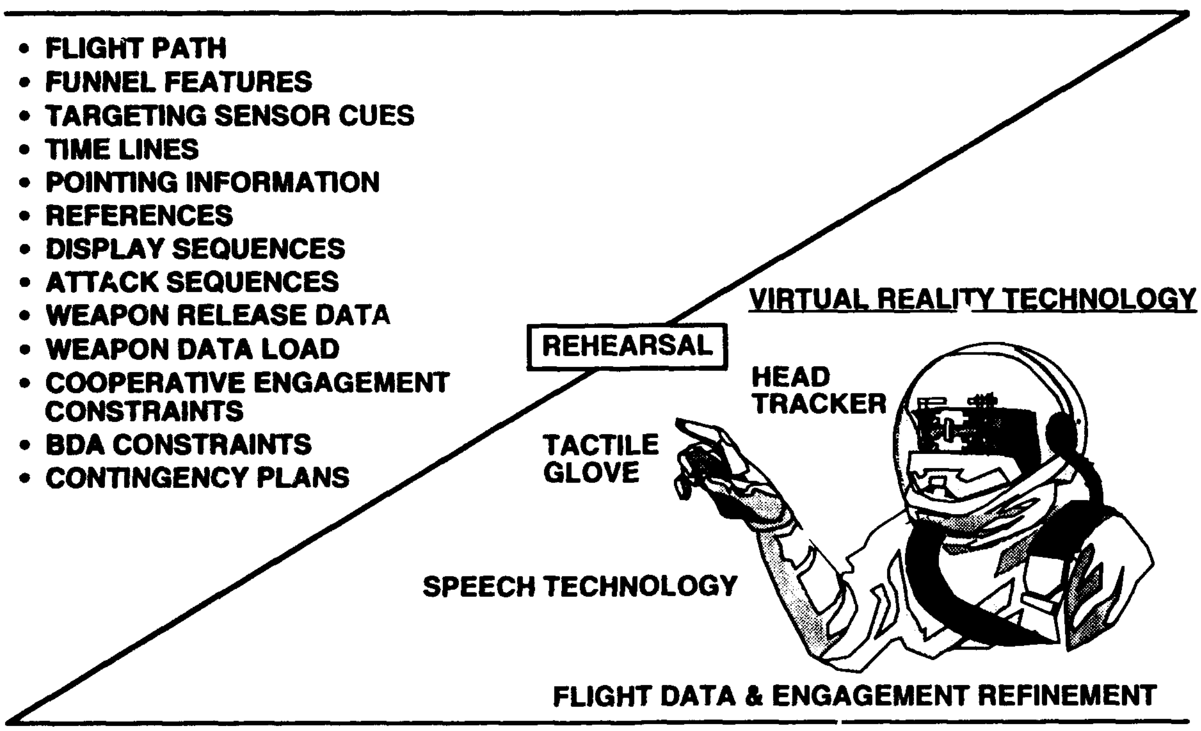

Fig 8. Mission Control and Rehearsal.

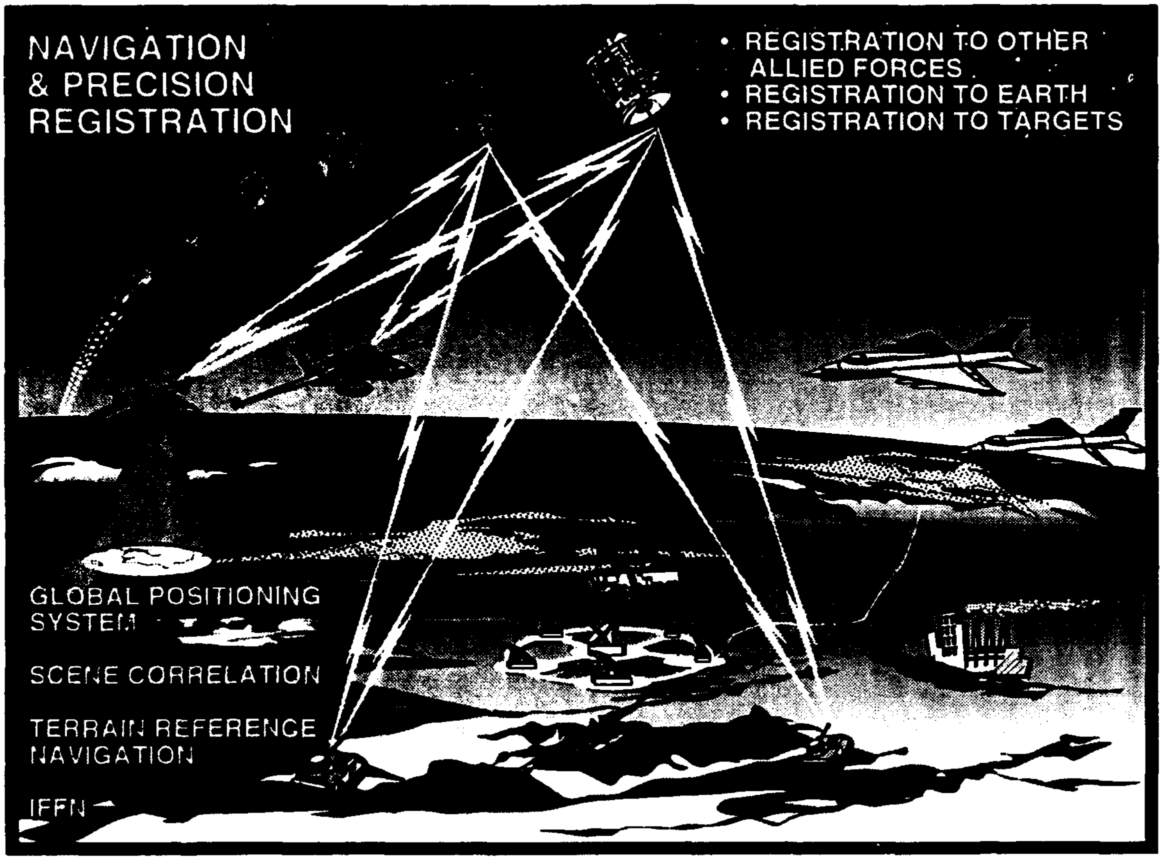

Fig 9. Navigation and Precision Registration.

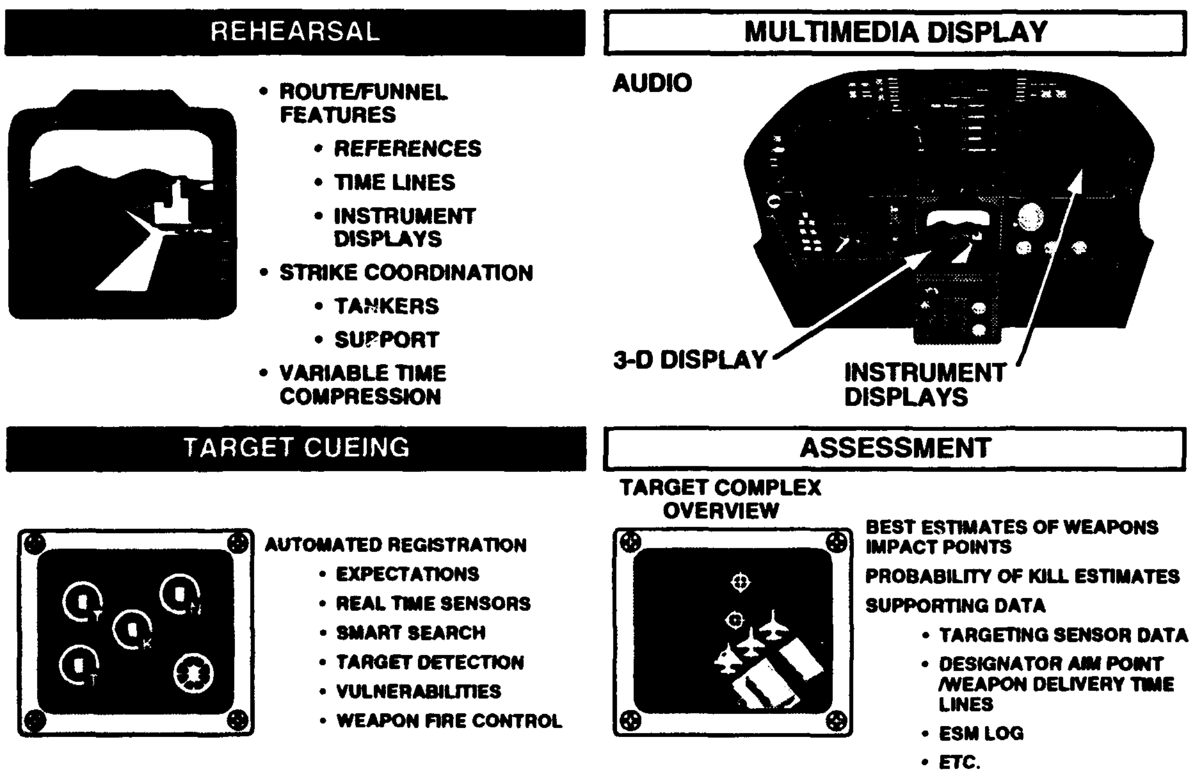

Fig 10 Rapid Mission Rehearsal/Attack and Assessment.

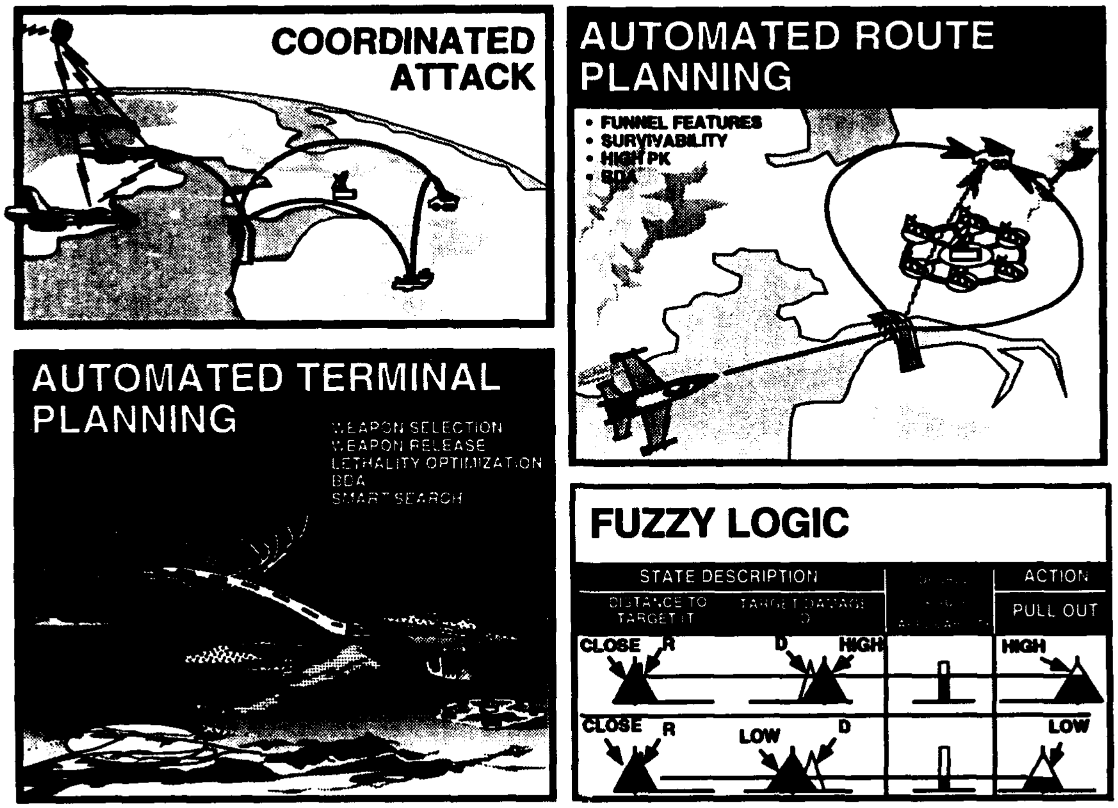

Fig 11. Adaptive Mission Control.

MISSION DATA BASE

- FLIGHT PATH
- FUNNEL FEATURES
- TARGETING SENSOR CUES
- TIME LINES
- POINTING INFORMATION
- REFERENCES
- DISPLAY SEQUENCES
- ATTACK SEQUENCES
- WEAPON RELEASE DATA
- WEAPON DATA LOAD
- COOPERATIVE ENGAGEMENT CONSTRAINTS
- BDA CONSTRAINTS
- CONTINGENCY PLANS

MISSION RECORD

- ANNOTATION OF DIFFERENCES
  - TIME
  - POSITION
  - ELINT
- AIRCRAFT/SENSOR POSITION/ ORIENTATION DATA
- BDA SUPPORT DATA
  - TARGETING SENSOR VIDEO
  - DESIGNATOR/WEAPON RELEASE TIMING/POINTING
- ETC.

Fig 12. Data Representation and Storage.

- EFFICIENT/EFFECTIVE CREW INTERFACING
  - WHAT AIRCRAFT AND PILOT NEED
  - HOW IT CAN BEST BE UTILIZED
  - CREW INTERFACE

  } DEFINES THE KNOWLEDGE BASE
- CORRELATED/INTEGRATED STRIKE DATA BASE
  - WHAT WE HAVE NOW AND IN THE FUTURE
    - DATA BASES
    - REAL TIME FEED
  - HOW TO CAPTURE THE KNOWLEDGE WE NEED
- EFFICIENT EXTRACTION OF DATA SUPPORTING RAPID (RE)TARGETING
  - HOW TO TRANSFORM DATA IN REAL TIME
    - COMPRESS/DECOMPRESS
    - SPECTRAL TRANSLATION
    - PERSPECTIVE, ETC.
  - HOW TO REGISTER DATA
    - MULTISPECTRAL
    - MULTISENSOR
    - MULTI-LOOK ANGLES, ETC
    - MULTI-CLASS – EOB, SURVIVABILITY, VULNERABILITY, LOCATION
  - HOW TO SORT/MERGE DATA
    - MOVING TARGET
    - SIZE
    - KNOWN/UNKNOWN
    - ETC.
  - EXPERT CONTROL

Fig 13. Strategy.

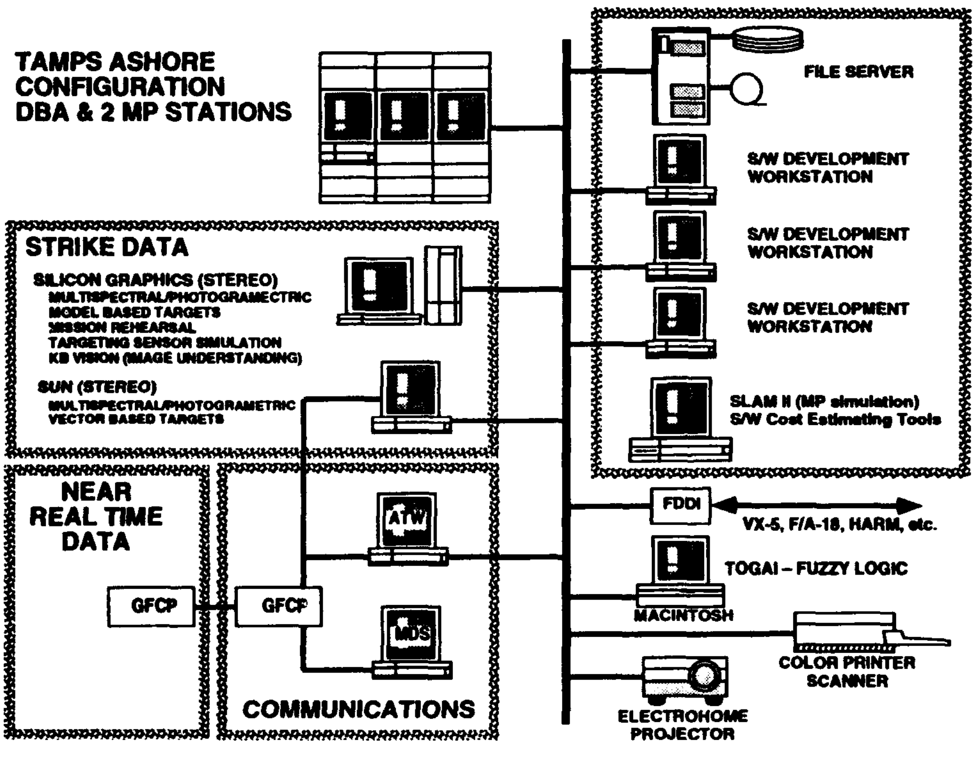

Fig 14. Strike Data and Mission Planning Laboratory Equipment Configuration.

Discussion

QUESTION M. JACOBSEN

What time is required for a typical mission planning using the tools presented?

REPLY

The tools presented are notional. Today's capability to support mission planning for a complex weapon system such as the Standoff Land Attack Missile (SLAM) takes several hours, so you would probably plan a mission the day before it is flown. The planning is not automated. For rehearsal of what the pilot will see when the seeker is turned on, the pilot is lucky if a photograph of the target is available.

QUESTION G.H. HUNT

What are the communications implications of the on-board planning/replanning concepts which you have described?

REPLY

The communications implications are significant. The potential area of response, for a loitering patrol aircraft, is hundreds of thousands of square miles. The initial data base requirements, as discussed in the paper, are beyond current storage technologies. The communications to support vectoring and changes to the data base could be prohibitive. Therefore our focus, which has been on defining the minimum information necessary to support strike operations, also minimizes the communications requirements.

QUESTION R. LITTLE

In the complex scenario which you have discussed, do you believe that a single-seat aircraft is feasible?

REPLY

Not for many years. Automation and expert systems are still a long way from the required performance levels to permit the replacement of a crewman with electronics.

MANAGEMENT OF AVIONICS DATA IN THE COCKPIT

by

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SUMMARY

The rapid developments in avionics and the associated processing power now available in aircraft have produced cockpit systems which can quickly saturate the crew with information.

Only by understanding man's capabilities and limitations will it be possible to design integrated avionics systems which match man's requirements and result in an effective man-machine combination.

1 INTRODUCTION

As successive new combat aircraft are introduced into service the quantity and complexity of avionics systems are progressively increased but man's information processing capacity has remained constant at a few bits of information per second.

Today's combat aircraft systems are directing many channels of information into the cockpit but the pilot is still the same single channel device that he has always been. It is now essential to "manage" the flow of information to the pilot to enable him to be provided with the relevant data, in a readily assimilable form at the appropriate time. This requires considerable cockpit automation to be incorporated into the avionics but at the same time, there needs to be an understanding of the requirements of the aircrew and, also the expertise that can be provided by aircrew which cannot, yet, be easily performed by automatic systems.

Future aircrew aids[1] such as the U.K.'s Mission Management Aid, the U.S.' Pilots Associate or France's Co-Pilote Electronique will only be viable if the information flow between the avionics systems and the aircrew can be suitably managed. This will be achieved by the use of many techniques which involve Task Analysis, Allocation of Function to man or machine, careful study of feedback mechanisms in both directions across the man-machine interface and validation by simulation and trials. Many attempts to do this have been made in the past with limited success. Somehow, the aircrew have made up for shortcomings in the avionics integration, but recent lessons learnt from the Gulf War and elsewhere have shown that the piecemeal approach to avionics integration has sometimes led to failure of the man/machine system and aircraft and aircrew have been lost.

Only by paying great attention to management of the information flow between aircrew and avionics systems will it be possible to optimise the man-machine system in future combat aircraft.

Examples of past problems and current developments in the management of data flow in the cockpit are given.

MAN MACHINE ATTRIBUTES

Not only have the number of systems in aircraft been rising over the years, (See Fig 1.) but the complexity of the individual systems has also been increasing. To offset these trends and to attempt to reduce the correspondingly high crew workloads in current combat aircraft, an increasing use is made of automation. However, just as most systems appear to have been developed separately and integrated at a very late stage in the development cycle, the application of automation often seems to have been applied in a random way and not always planned as an integral component of the man-machine system.

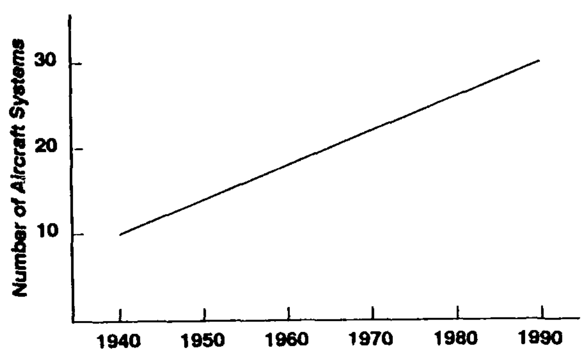


Fig 1. Growth in Combat Aircraft Systems with Year in Service

Rarely are the relative merits of the man and the machine compared to indicate which tasks should be allocated to the man and which tasks to the machine or automation[2]. Fitts, as long ago as the 1950s, listed a number of qualities which are performed best by man or machine (See Table 1.) yet little of his philosophy appears to be implemented in military cockpits as the 21st century is approached. For example, only a few years ago, it was found in a new aircraft weapons system that the only links between the radar, the navigation

TABLE 1

FITTS' LIST

Quality	Machine	Man
Computation	Accurate, fast. Poor error correction.	Slow, inaccurate but good at error correction.
Complex activities	Multi-channel	Single channel. Time sharing.
Consistency	Precise repetition	Unreliable. Needs monitoring.
Intelligence	Limited at present	Can deal with the unpredicted and can anticipate
Manipulation	Good at specific tasks.	Great versatility.
Memory	Good literal reproduction.	Large store, multiple access. Best for principles & strategies.
Overload	Sudden breakdown.	"Graceful degradation".
Power	Wide range. Consistent.	0.2 h.p. for continuous work. Variable.
Reasoning	Good deductive.	Good inductive.
Speed	Wide range. Consistent.	1 second lag.
Sensory input	Wide range, some outside human senses. Can be made insensitive to other stimuli.	Wide energy range and variety dealt with by one sensor. e.g. eye deals with location, movement, colour. Good pattern recognition. Good detection in noise. Upset by environmental factors such as noise, vibration etc.

and the weapons system were through the man[3]. To estimate the speed and direction of a surface vessel, the crew member had to place cross wires over the blip on the radar screen and then read off a range and bearing. This was fed manually by keying into the aircraft's navigation system which converted the data into a grid position,read off and then plotted manually onto a chart. This procedure was repeated a minute later. Speed and direction were then estimated from the distance between the two spots marked on the chart. This was an extremely tedious, inaccurate and time consuming process for the man which prevented him from performing more important mission management tasks. Thus, it was the man who provided the system integration even though the radar and navigation systems could have been hard wired together relatively simply and cheaply. This is a typical example of how different systems can be developed separately with little consideration given either to their integration or to making the best use of the man's unique decision making abilities.

Even when a decision has been taken to allocate some functions to be done automatically, a further decision needs to be taken over whether the man should be given the opportunity to intervene or merely monitor the automatic process.

On the one hand, if the man decides to take over a task which is normally done automatically and with which he is out of practice, he may well reduce performance or exacerbate an already dangerous situation. Alternatively, a situation which was not envisaged when the automation was designed may be encountered for which automation cannot cope, yet the man, through inductive thinking can find a solution. For example, some years ago a three-engined jet airliner's all-moving tailplane mechanism failed and the auto pilot was left with no attitude control. By application of their past experience the crew were able to save the situation by using differential thrust between the rear fin mounted engine and the underwing engines to maintain the required attitude and to land safely. There is no way that automation could be planned to correct such an unusual and unexpected situation.

2 Transmission Rates and Information Load

There is almost no limit to the information transmission rate for which a machine can be designed, yet man's evolutionary process has resulted in him having a transmission rate of only a few bits/second. Fig 2. contrasts the unchanging low information transmission rates for man with the increasingly higher rates that are being developed for machines. Man's useable channel capacity, depending on the method of encoding used, is generally between about 2-25 bits/second, regardless of the channel employed[4]. This results in an obvious mis-

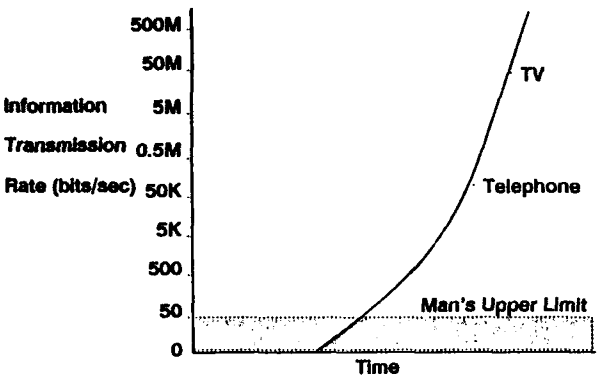


Fig 2. Comparison of Man and Machine Information Transmission Rates with System Evolution

match between the man and the modern cockpit system's information handling capacities of many millions of bits/second.

In addition to the aircraft's basic systems such as flight control, fuel, weapons etc, the next generation of aircraft could have a suite of sensors and communications links. These could include Radar, Radar Warning Receivers, Infra Red Search and Track, Missile Approach Warner, Radio Altimeter, Terrain Following System, Cable Warning, Laser Warning Receiver, Night Vision Aids, Data Links, UHF and VHF radios. While the crew can cope with one or two sensors and systems at a time, some form of machine intelligence in the form of a mission management aid will be required to filter the information and to schedule it in a timely and appropriate way to the crew.

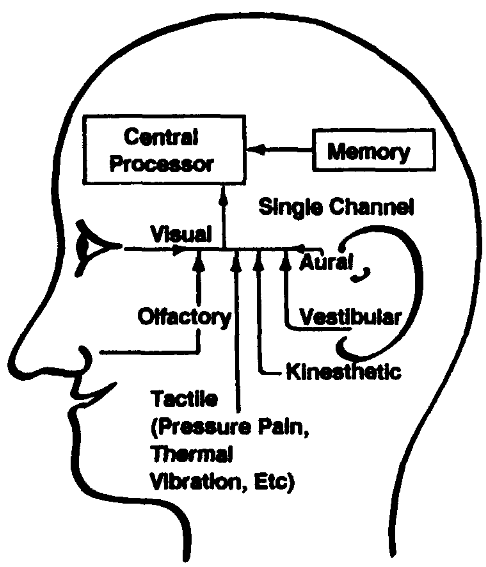


Fig 3. Man's Single Channel for Sensory Inputs

Although man can be considered as a multi-sensor device, the link between his sensors and the "central processor" part of his brain can be likened to a simple channel which accepts information from only one sensor at a time. This concept is depicted in Fig 3. If it is assumed that the human operator receives and processes information in this way, it can be argued that the information from different senses must be time shared. This, together with the limited transmission capacity re enforces the theme of this paper that too much information should not be presented to the man.

If the signals reaching his sensors are degraded by noise or other environmental effects, his workload will be increased and his ability to process the information presented will be still further reduced. Fig 4. depicts both the information sources and some of the factors which degrade man's ability to sense the process signals. Only by carefully matching information sources to the man's processing and channel capacities will the optimum man-machine system be produced.

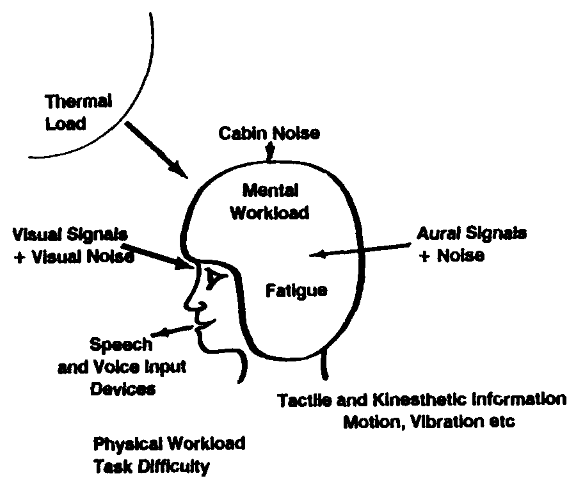


Fig 4. Contributors to Crew Workload

One method which attempts to overcome the mis-match in information flow between machine and man is that of increasing the size of the crew.

For example, long range maritime patrol aircraft often have a crew of 10 or more to operate and integrate the many systems required for Air Sea Warfare (ASW). An ASW aircraft crew typically comprises:-

2 Pilots for flight control and systems management
2 Navigators for routine and tactical navigation
3 Underwater Sensor Operators
1 Radar Operator
1 Electronic Support Measures Operator
1 Magnetic Anomaly Detection Operator/Despatcher
Total 10

Even with this crew size, there are often workload peaks which are beyond the crew's capacity to handle effectively. One solution that is often applied to overcome this problem is to add one or more additional crewmen. This tends to be an ineffective and costly remedy since it exacerbates one of the original causes of the problem, which is that of communication overhead.

With a multi-crew aircraft, an appreciable amount of effort is spent in communicating between crew members. The proportion of this overhead increases as the crew number increases in the ratio of

$$\frac{n^2-n}{2}$$

where n is the number of crew.

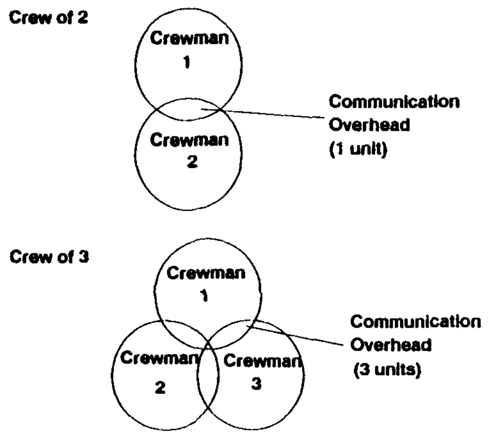


Fig 5a. The Effect of Crew Number on Communication Overhead.

This is illustrated in Fig 5a. With a crew of 2, some effort is required for communication between them. With a crew of 3, the communications is trebled and with a crew of 4, 6 times the overhead is incurred, ten times with 5 crew, fifteen times with 6 crew and so on. Thus as the number of crew increases, the proportion of the communications overhead increases at a greater rate. This is, of course a very simplistic model which does not take account of the following two opposite effects. Firstly, not all crew members may need to communicate regularly with all of the others.

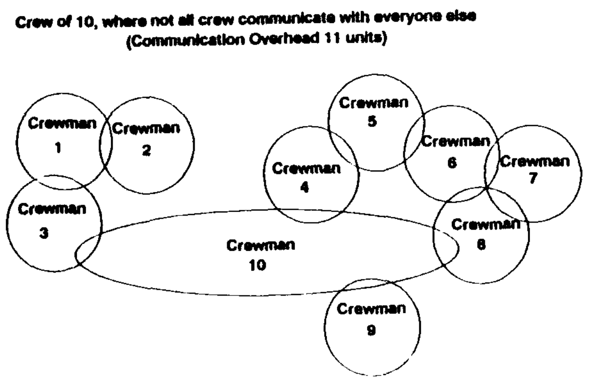


Fig 5b. The Effect of Crew Number on Communication Overhead.

Secondly, in long, relatively narrow fuselages, as additional crew members are added they and their associated equipment have to be positioned further and further apart along the length of the aircraft which increases the difficulty in communication. (See Fig 5b.) Conversely, if the number of crew can be reduced by automating some of the tasks, the communications overhead will be reduced and the workload will also diminish.

3 FUNCTIONAL ANALYSIS OF A MISSION

A clearer understanding of the information flow within the cockpit and an appreciation of both the man's and the machine's merits and shortcomings is required if anything near the optimal solution is to be achieved.

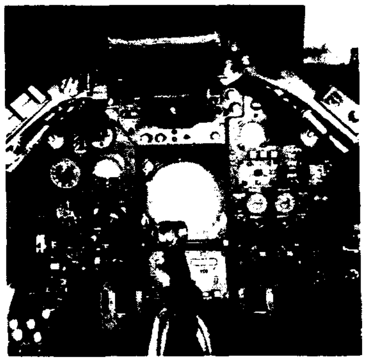


Fig 6. Fast Jet Cockpit of 1960's with Electromechanical Instruments

In the past, cockpits were full of electromechanical instruments and each instrument was dedicated to a specific system. Fig 6. shows a typical fast jet cockpit of the early 1960s where the crew had fewer systems to monitor; where mental and not physical action was needed to select information. Contrast this with Fig 7. which shows a typical modern fast Jet cockpit layout.

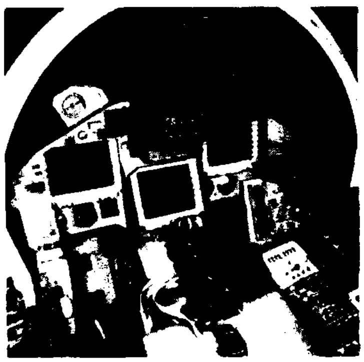
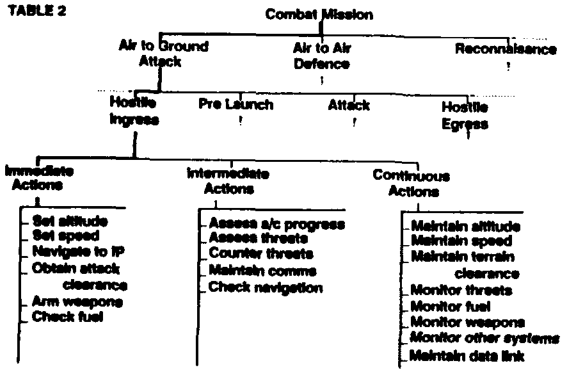


Fig 7. Typical "Glass" Cockpit of Today

This is dominated by just 3 multi-function CRT displays, a HUD, and a few standby electro-mechanical displays. It is a much simpler and neater cockpit layout. It has, however, the potential of presenting orders more information to the crew during a mission. To ensure that the correct information is presented at the right time, either the pilot has to select the information himself or have the information selected automatically for him by the system. In a "real life" dynamic situation a mix of the two approaches probably will be required. To achieve the right balance in this area a functional analysis of the mission is required. This will successively break down the mission into smaller and, more detailed items. For example, for a combat aircraft the mission will break down as shown in Table 2.

TABLE 2



First of all the type of mission is selected. In this case an Air-to-Ground mission has been broken down into the phases of Hostile Ingress, Pre-Launch, Attack etc. Each phase is then sub-divided into Immediate, Intermediate and Continuous Actions. These are further separated into functions such as "Set altitude and Speed," "Assess threats" etc. These functions can be examined in further detail to identify objectives and tasks. For example, to set Ingress Altitude and Speed, the aim must be to proceed as swiftly as possible (since the enemy may have been alerted). Throttle settings will have to be reset and altitude altered depending on information received by data link or other sources.

Thus, this process of task analysis progressively decomposes a defined mission into phases, segments and tasks. It allows a clearer understanding to be made of the component parts of the mission at a very detailed level. It enables the information available from the system to be compared with that required by the crew at a specific time and any mismatch in desired information flow to be identified. It then allows task synthesis to be used to rebuild a mission for a future system in which tasks can be re-allocated to man or machine, depending on their relative attributes.

4 RULES FOR THE MAN IN THE MAN/MACHINE SYSTEM

Remember that man is effectively a single channel device which must not be overloaded. Therefore:

1 Do not overload the man by
   a. giving him too much information
   b. giving him unnecessary information
   c. giving him calculations to do that can be done faster and more accurately by a machine.

2 Do not give the man uninteresting repetitive tasks.,

3 Do not give him monitoring tasks where he is unalerted but looking for rare events.

4 Where possible, give the man tasks that he enjoys doing and is good at. Give him enough to occupy him but still leave him with enough spare capacity to deal with unexpected events.

5 Use the man's inductive thinking ability to deal with unplanned events which cannot be automated.

5 CONCLUSIONS

Man is relatively poor at handling information and is easily overloaded. Information from systems and sensors needs to be processed, filtered and presented to him at the appropriate time. Some form of mission management aid which automates the functions that he is poor at doing is required. Despite man's limitations, he has some attributes which cannot yet be reproduced by machine intelligence. It is essential, therefore, to allocate the various component mission functions to either the man or machine, depending upon which has the appropriate attributes.

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Model-Based Reasoning Applied to Cockpit Warning Systems

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Summary.

With the advances in display technology and the increasing use of software control more information in the modern commercial aircraft cockpit is available on request only instead of continually. Furthermore, the reduction in crew size has resulted in a reduction in the routine monitoring of system parameters. However, advances in sensory capability are enabling far more system parameters to be measured. The combination of these trends leads to the perception by the aircrew of an abrupt transition from normal operation to the need to deal with system malfunction. This paper outlines some work undertaken to maximise the use of available information in order to maintain the aircrew's awareness of the status of the aircraft's systems and to provide advice in the advent of malfunction or abnormality. The appropriate carrier of such information is the modern centralised cockpit warning system.

Introduction.

With the advent of CRT-based software controlled display technology there has been a decline in the number of displays fitted to civil aircraft over the last ten years. Consequently there has been an increase in the amount of hidden information which, while available on request, is not automatically displayed. This loss of information has been compounded by the reduction in crew numbers from three to two i.e. the loss of the flight engineer, resulting in a reduction in the routine monitoring of system status in these aircraft. At the same time there have been advances in sensor technology, in particular the development of optical sensors, which have provided the ability to measure system parameters with greater accuracy and system parameters which previously could not be measured because of hostile environmental conditions.

The result of these advances is that, while there is increased measurement of system parameters there is less capability in the cockpit to monitor system status and trends. As a consequence, when an emergency does occur the aircrew are less prepared to respond in the correct manner. This is compounded by other advances in cockpit technology, e.g. flight management systems, which have reduced crew workload but potentially also reduced crew awareness of the aircraft's state.

As part of the process of reducing crew workload aircraft warnings and cautions have been integrated into a central warning system which is usually combined with a display of primary engine parameters. The purpose of these systems is to locate all aircraft system information in a central position; audible warnings direct the crew's attention to the central warning system which indicates the problem and re-directs attention to the specific system.

This paper describes some aspects of work undertaken towards the proof-of-concept of an Advanced Cockpit Warning System (ACWS). This system is based upon making better use of the information available by monitoring aircraft systems' status and trends and integrating the results to achieve not only local system monitoring but, more importantly, a view of the aircraft's situation as a whole. There are clearly two distinct but related parts to this work, namely the processing of data and the display of information. This paper is concerned with the data processing aspects of the system, the HCI aspects are addressed in [1].

State of the Art.

Although there are minor differences between aircraft types the basic layout of modern central warning systems is similar. They consist of two CRT screens set one below the other; the upper carries the primary engine data together with an area for the display of colour coded warnings; the lower carries, upon selection, either an extension of the upper display or a synoptic diagram of one of a set of aircraft systems e.g. hydraulics, brakes etc.

The colour codeing of the warning messages is typically red for immediate action, amber for action to be taken in the near future and some other colour, often magenta, for advisory information. Indentation may also be used to indicate different degrees of urgency within the amber band. The warnings are prioritised according to this colour codeing and, within each code, according to the time of receipt.

When a red warning is received immediate action must be taken; there is no time to supply additional information. On the other hand, when an amber warning or advisory information is received there is a time-window of undetermined duration which can be used for the provision of additional information and the delay of action. Informal discussion with aircrew has indicated that it would be desirable to use this opportunity to provide information about the consequences of taking the appropriate action before it is taken i.e. what systems will be lost when the action is taken.

Once a warning message has been received the action or actions to be taken are set out under standard operating procedures. These are defined by the Flight Operation Manual and the associated Quick Reference Handbook. These manuals, to which the aircrew refer in the event of a malfunction or abnormal behaviour, are designed by the aircraft manufacturer and the airline and have been certified by the appropriate authorities. Also the aircrew have been trained to respond to situations according to this set of rules. There is therefore

a well-defined procedure to be carried out for each malfunction.

The codeing and prioritisation method outlined above is adequate for single warnings or simple situations in which several warnings appear. Difficulties can arise though in complex situations where a number of failures have occured (multiple-source/multiple effect) or when a failure has resulted in a number of consequent failures malfunctions or abnormalities (single-source/multiple effect). Under these conditions the number of warnings and advisories combined with the pressure to respond and the rapid transition from a normal to an abnormal situation, can cause confusion leading to inappropriate actions being taken. In the case of multiple-source multiple effect failures the difficulties are compounded. Not only is too much information supplied but also, once the causes have been ascertained it is necessary to devise a set of actions which will allow all failures to be rectified i.e. actions taken to rectify one failure must not inhibit remedial action being taken for another.

The requirements for an effective ACWS are derived from the above discussion. It is intended that the resulting system performs the following functions:

- long-term monitoring of the type previously undertaken by the flight engineer;
- the identification of primary causes of abnormal conditions paricularly in cases of multiple effects;
- the provision of remedial actions, and their consequences;
- a reduction in the occurence of false warnings;
- maximisation of the time between the detection of abnormalities and the occurence of emergencies.

System Overview.

The system being investigated is based upon the integration of a set of real-time monitoring systems; each such system is responsible for its local monitoring and an executive function integrates the output of the set. As such it has three principle components (see Fig.1).

At the lowest level, receiving data from the aircraft systems, is a network of nodes. Each node is a monitoring system responsible for assessing the status and trends of the output parameters of the aircraft system which it represents. To do this each node contains a model of the system it is monitoring together with an assessment function which is able to report on the status and trend of the output parameters of the real-world system. The nodes are linked to each other in a manner which represents the transfer of physical parameters from one aircraft system to another.

The nodes report system status to an executive function, the network executive, which combines the information it is receiving to form a view of the overall situation. From this view the executive forms a plan, an ordered set of actions, derived from standardoperating procedures, to ameliorate abnormalities, rectify the effects of malfunctions and maintain the safe operation of the aircraft.

The third component of the system is the display. Work is being undertaken [1] in this area to ascertain the difficulties encountered with the current display layout and the difficulties that will be encountered when additional information of the type produced by the proposed system is available.

System Operation.

As each node monitors its associated real-world system it uses its model to take inputs from its connected nodes and produce values of its output parameters. Each of these is compared to the sensed values of the parameters and, if a discrepency is detected, a report containing status and trend information is passed to the executive function. Both the sensed parameter values and the reports are passed on to the connected nodes. In this way a node is aware of the quality of its inputs and any detection of fault can automatically be ascribed to the system being monitored. In this manner two of the ACWS requirements are met; by contiuously monitoring individual parameters long-term effects such as a slow oil leak can be detected sufficiently early for appropriate action to be taken; by interlinking the monitoring systems the distinction between cause and effect can be established, thereby resolving the confusion resulting from the over-provision of information.

In the case of a single-source malfunction the executive is required to look up the appropriate actions, derived from the standard operating procedures and pass them on to the display. Before doing so it may also check the report by searching for confirmatory data among the other reports it has received. This will have the effect of reducing the number of false warnings. In the more complex cases of multiple-source malfunctions the executive must order the set of actions which is composed of all actions for each malfunction as derived from the standard operating procedures. In each case the executive can use the network of nodes as a resource to investigate the consequences of particular actions or orderings of actions. In this manner other system requirements are fulfilled i.e. prediction of the consequences of taking an action before it is taken.

Model-Based Reasoning.

The use of models to represent and understand situations, events and systems has been a key feature of many diagnostic systems developed in the field of Artificial Intelligence (AI). The model-based approach to reasoning can be seen as the basis of many common-sense reasoning tasks.

Models can be used in two distinct ways. The first is as a tool or method for containing our understanding of the real world. In this case observations which do not accord with the predictions of the model are assumed to require a revision of the model. This is essentially the mechanism by which we attempt to understand the natural world through science, improving our understanding through observation and refinement of our models.

In the second case the model is assumed correct and observations of a real-world system which do not accord with the model are assumed to be symptoms of a malfunctioning of the corresponding real-world system. This is essentially the diagnostic use of the model. Within this category a number of systems have been developed. There

are those in which models represent the symptoms of a malfunctioning system; medical diagnostic systems such as MYCIN [2]. Such systems contain only known symptoms derived from human expertise. In consequence they are clearly unable to diagnose any malfunction which has not already been recognised. This limitation extends to being unable to perform a diagnosis when the symptoms of more than one malfunction are observed simultaneously. These models lack the "deep knowledge" to allow reasoning from first principles.

As a result of the limitations of these expert systems interest has recently turned to diagnosis from first principles using models which represent the behaviour of the correctly functioning real-world system [3], [4], and [5] for example. In systems such as these observations which conflict with the model cause diagnosis to be undertaken usually through the use of a heirarchy of models. While there are no discrepencies at the top level only the top level model is used; when a discrepency is found at that level the next lower level models are checked. This process continues until a model at the lowest level is found to be faulty i.e. the cause has been identified and action can be taken. In the case of multiple faults this process can become complex although the principle is the same. Within such an approach it is necessary to determine the level of detail to which the modelling need be taken and this in turn can be determined by the actions which will be taken to rectify the situation. For example, if the remedial action is to replace a unit in a system then there is no purpose in modelling the internals of that unit; it is sufficient to identify which unit is faulty.

This approach to modelling is the one which has been adopted for the ACWS. Since the nature of the remedial actions which can be taken by the aircrew in response to a malfunction are limited (usually confined to reducing use of the equipment in question or turning it off entirely), the system is required to identify malfunctioning systems but it is not required, at present, to undertake thorough diagnosis. Consequently there is little purpose in diagnosing to a level lower than that which is useful for the aircrew. Furthermore it can be assumed that, for the majority of its operation, the ACWS is confirming that the systems it is monitoring are behaving normally and it would be fruitless to expend considerable computing power running detailed models to confirm this. It follows then that the models need to be sufficient to detect abnormal behaviour and place some measure on it but do not require the level of detail that would be required for an on-board diagnostic system. If, at later stage the ACWS were to be extended to an on-board diagnostic and maintenance system it is highly probable that simple models, similar to those currently employed, would be used for detecting abnormalities and that advice to the aircrew would be given on the basis of these models while more complex models would be used for detailed diagnosis which could be undertaken as a background task once the safety of the aircraft had been established.

The Use of Models for Monitoring.

Within the ACWS application the types of parameters to be monitored can be broadly divided into two classes. There are those which should have a constant or almost constant value throughout the operating cycle of the aircraft; an example of this type of parameter would be the oil quantity in an engine. Monitoring these parameters requires assessing whether any changes are occurring to the value and whether such changes constitute a trend. In this case the model used for monitoring could be quite simple although some complexity is added when the start-up and shut-down phases of the operating cycle are included.

The second category comprises those parameters which are in some manner dependent upon the values of some input parameters; in the engine the turbine rpm could be said to depend upon the combustion gas temperature. In such cases only the extremely high or extremely low values of the parameter constitute abnormalities in their own right. Between these extremes an abnormality is a mis-match between the values of the input parameters and the expected values of the output parameters.

The task of monitoring aircraft systems within the ACWS is based upon the comparison between real-world values of parameters, derived from sensory apparatus, with expected values of those parameters derived from a model or models. The value of a parameter is described as either too high, too low or normal. A detected discrepency will be tracked to determine its trend which is categorised as one of:

- convergent - the situation is improving;
- divergent - the situation is deteriorating;
- stable - the value is too high/low but neither improving nor deteriorating;
- oscillating - the situation is unstable.

Rather than use computationally intensive detailed models of the systems to be monitored the approach used to meet the requirements of the system is to base the model upon a set of relationships between parameters which are derived from data from the particular system to be monitored, and an understanding of how such a system functions. In the case of an engine a part of a simple model could be of the form:

If FUEL-FLOW is HIGH
then TURBINE GAS TEMPERATURE is HIGH.

Such a model is too simple; it does not consider the rate of change of either parameter but it could be extended to do so. It can, however, identify an abnormal condition if say Fuel Flow was seen to be high but Turbine Gas Temperature was detected as not being high. This is a model of correct behaviour rather than a description of a particular failure condition; any pair of Fuel Flow/Turbine Gas Temperature values which does not accord with this model could be described as abnormal in the sense of not complying with expected behaviour. Hence normality and, consequently, abnormality are detected quickly by determining the truth of the statement for any given pair of values.

In order to establish the trend of any discrepency it is necessary to assign some value to it. In the above example that would mean having some measure of the degree to which Fuel Flow is HIGH and Turbine Gas Temperature is HIGH. Therefore a classification mechanism is required. This mechanism is supplied by the use of fuzzy logic.

An Overview of Fuzzy Logic.

Fuzzy sets were conceived of as a method of representing classes of objects found in the real

world which do not have precisely defined membership criteria. Upon consideration this can be seen to cover a wide range of classes of object which play an important role in human thinking and decision making processes. For example, the "set of tall men" is an adequate definition of a class which can be reasoned about in a manner such as, "tall men need to buy large size clothes". It would be difficult, and possibly misleading, to attempt to define "tall men" and "large size clothes" in too great a detail and such detail is not necessary for our understanding of the statement. This is the type of categorization required by the models in the ACWS in order to perform the monitoring task.

Since the introduction of fuzzy sets by Zadeh in 1965 [6] the concept of fuzzy logic has been developed and applied in a wide range of fields. Initial work was involved in making more rigorous the formulation of the theory including constructing common definitions of the usual set operations (see [7], [8] for example). However, it became clear at an early stage of development that fuzzy set theory had applications to control problems and a number of experimental systems were developed across a range of application domains e.g. [9],[10]. The use of fuzzy control has now reached the market place in Japan and China with the Japanese electronics industry replacing conventional control systems with fuzzy control systems in a wide range of products. These include consumer appliances such as washing machines, video cameras and vacuum cleaners as well as many industrial applications such as failure prediction for machine tools, the control of automatic trains [11], the control of crane operations [12], and the control of water quality [13].

A fuzzy logic controller has at its core a model which is composed of a set of production rules familiar to designers of expert systems. Such rules are of the form:

IF x is A_1 and y is B_1 then z is C_1;

IF x is A_2 and y is B_2 then z is C_2;

IF x is A_3 and y is B_3 then z is C_3.

A rule may have more antecedents and more complex logical relations. The membership of x in the sets A_i (where i = 1, 2, or 3 in this example) and the membership of y in the sets B_i is determined from the use of fuzzy set membership functions. The purpose of the rules is to determine an appropriate value of z by inferring its membership value in the sets C_i, from the membership values of x in the sets A_i and y in the sets B_i. This is the type of model employed in the ACWS. The model itself is independent of the way in which values are distributed over the sets i.e. it is a description of the interaction between parameters. The parameters are ascribed set membership on the basis of data and an understanding of the system under consideration.

An example of assignment of parameter values to fuzzy sets is shown in Fig.2 where the parameter under consideration is height and the value being assigned is 5.0. The sets in Fig.2 can be described as:

SHORT:	$f_1(h) = 1.0,$	$h < 4.8,$
	$= (5.8 - h),$	$4.8 <= h <= 5.8;$
AVERAGE:	$f_2(h) = (h - 4.8),$	$4.8 <= h <= 5.8,$
	$= (6.8 - h),$	$5.8 <= h <= 6.8;$
TALL:	$f_3(h) = (h - 5.8),$	$5.8 <= h <= 6.8;$

and the assignment of 5.0 is then:

SHORT: 0.8;
AVERAGE: 0.2;
TALL: 0.0

providing a classification of this value.

Monitoring within the ACWS.

The monitoring process in the ACWS is composed of three elements; a fuzzy set classifier, a rule-based model and a comparison function. These are illustrated in Fig 3.

The fuzzy set classifier takes the value of a parameter and assigns a distribution over the five sets EXTREMELY-LOW, LOW, MEDIUM, HIGH and EXTREMELY-HIGH. This distribution is represented as a five-element vector of the form:

$$(0, 0, y, 1 - y, 0)$$

where the sum of the elements is 1.0 and non-zero values are assigned to two adjacent components. Thus a value of a parameter derived from the sensors is converted into a description of the value. In a similar manner changes in the value over time are reflected in changes in the degree of membership of each of the sets. The classifier is unique to the system being monitored and the shape of the sets is derived from data from that system e.g. classification of turbine gas temperature may be slightly different for each engine on the aircraft although the engines are nominally the same.

The rule-based models are adapted from those used by fuzzy control systems as described above. In this case, rather than deducing an output value the model produces an output distribution such as

$$(0, 0, z, 1 - z, 0)$$

from an input distribution e.g.

$$(0, 0, x, 1 - x, 0).$$

This achieved by using rules of the form:

```
TEMPERATURE is LOW
    to degree FUEL-FLOW LOW
        if FUEL-FLOW is LOW and STABLE
        or FUEL-FLOW is LOW and INCREASING
    to degree FUEL-FLOW EXTREMELY-LOW
        if FUEL-FLOW is LOW and INCREASING
        or FUEL-FLOW is EXTREMELY-LOW
```

etc., one set for each of the five categories. The model describes the behaviour of a system and so is common to all such systems e.g. an engine model is the same for all engines.

Comparison is performed by examining the difference between the distribution produced by the classifier and that produced by the model. The contrast between the distributions is:

$$(0, 0, z - y, y - z, 0).$$

The magnitude of the difference is $|z - y|$ and the sign of $z - y$ determines whether the value is higher or lower than expected. Clearly with $|z - y|$ close to 0 the parameter is behaving as expected and no further action need be taken. If, however, $|z - y|$ is not close to 0 then, potentially, an abnormality is developing and the changes in $|z - y|$ are monitored to determine whether the deviation is deteriorating, improving

or stationary. Also the rate of change in the value will indicate the speed at which changes are occuring.

Propogation through the network of models is effected by passing the distribution derived from the sensed value to the connected nodes for use in their own models. It is intended that the network can also be used to predict the outcome of actions. This can be achieved by supplying assumed values or distributions to the node with the model supplying the consequent output to be passed on to its connected nodes. In this way the affects of actions on the overall system can be determined before those actions are taken.

This division of the processes allows one monitoring mechanism to be employed on all models of all systems since parameter values are mapped into the range 0 - 1 by the classifier. It also allows for substitution of components since the model of the behaviour will be unchanged but the classifier will be amended in accordance with data derived from the replacement system.

Progress and Results.

Using the above methods a model of an engine has been produced which is composed of three sub-models; a three-stage compressor, a burner and a turbine. These models monitor six primary parameters, fuel flow, turbine gas temperature, rpm, and low, intermediate and high pressure spooler speeds. Initial results are promising: this simple network is capable of detecting and establishing the trend of the onset of an exceedence in spooler speed during take-off some 10 seconds before the exceedence occurs. This set of models is being refined and extended to include the monitoring of complimentary parameters e.g. intermediate pressure and temperature measurements. One such network will be required to represent each engine on an aircraft.

The proof of concept stage of the project has a further two years to run. It is intended that at the end of this stage there will be models of the engines, the fuel system, the electrical system, the hydraulic system and the flight control system. In parallel with this activity the other aspects of the ACWS, the executive function and the interface, will be developed.

Acknowledgements.

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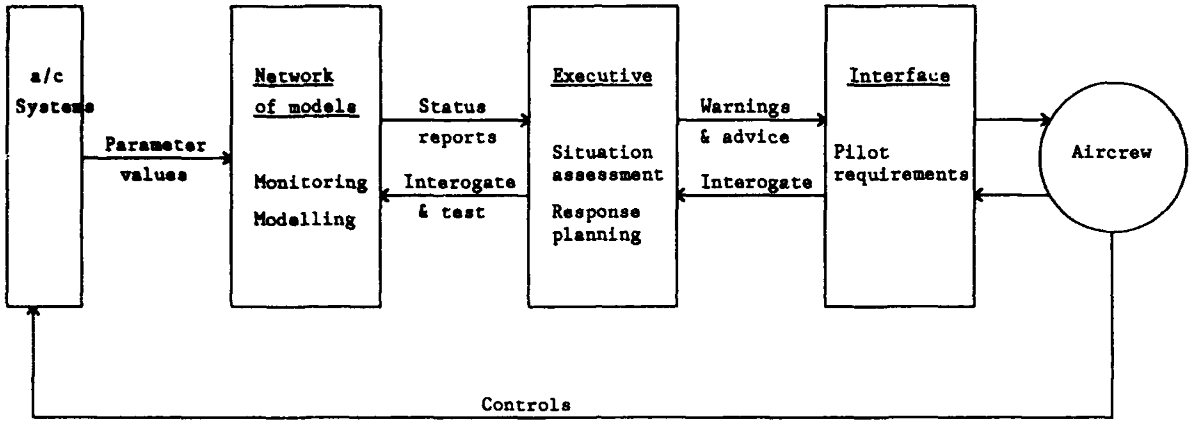

Fig 1: System Functionality.

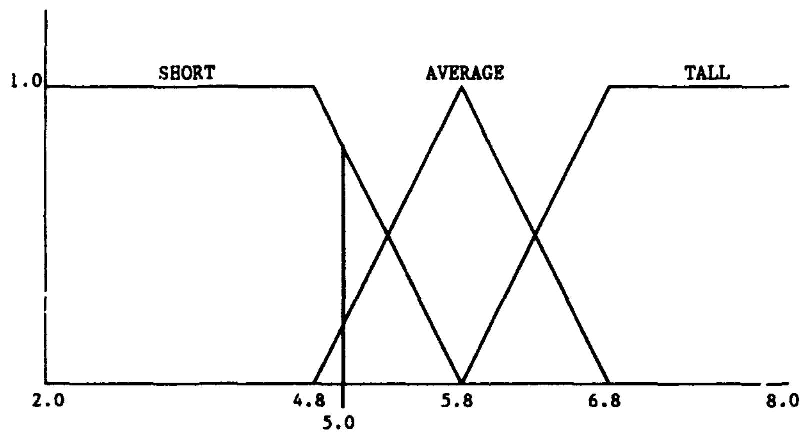

Fig 2: Classification of Height.

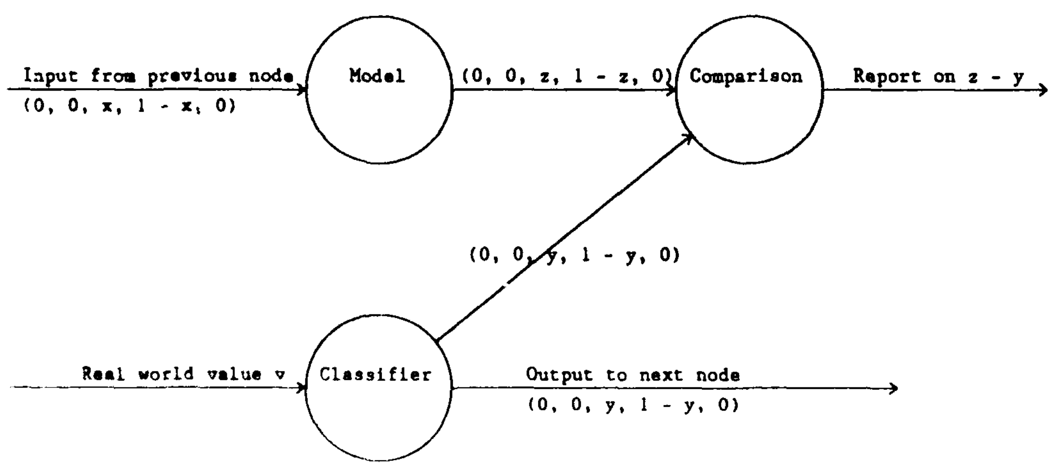

Fig 3: Node Operation.

Discussion

QUESTION R. LITTLE

How can we certify these systems to the high levels of integrity required in civil aviation?

REPLY

The need is recognised, but not enough work has yet been done in this area.

QUESTION R.M. TAYLOR

You referred to the necessity of using relatively simplified models of complex systems. How do you evaluate and validate whether the model is necessary, sufficient and adequate for the task?

REPLY

The models are derived from available data and from a basic understanding of the system being modelled. The derivation of models is essentially data driven; they are validated against other data sets relating to the same system.

THE INTEGRATION OF ADVANCED COCKPIT AND SYSTEMS DESIGN

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SUMMARY

This paper examines how typical operational scenarios that are representative of future conflict impact on the specification and design for man/machine performance. Operational Requirements for aircraft to survive and deliver the goods in this context present a tremendous challenge to the Prime Weapon System Contractor.

Military procurement agencies have long been striving to realise increased weapon system performance from dwindling resources. Thus current initiatives such as MANPRINT have been launched to change an equipment-oriented view of system development towards a broader view that considers hardware, software and operator together as a system.

It is argued that unless the piloting function and system integration tasks are considered as an integral part of the design process from day one, a less than optimum design will always result. It is recommended that a structured top-down design methodology be employed that translates Operational Requirements into piloting and system functions at one and the same time.

An overview is given of use of just such a design process developed at BAe Warton, with particular reference to the European Fighter Aircraft (EFA) project. The various stages of the design process are explained and indications given of current progress on EFA. Emphasis is given to the tools and methods used to ensure that a highly integrated system and advanced cockpit design are successfully achieved.

1 INTRODUCTION

Predicting the scenario of the next conflict in which Western aircraft will be expected to operate is becoming increasingly difficult. The demands on the next generation of fighter/attack aircraft are for an unprecedented level of agility, performance and lethality combined with flexibility and adaptability.

This aircraft is expected to combine the roles of both the InterDictor Strike (IDS) and Air Defence Variant (ADV) of Tornado, outperform the F15/F16, be more versatile than the F18, be so stealthy as to be almost invisible whilst remaining a single-seat aircraft. The ability of the pilot to manage the demanded task with the provided vehicle is therefore a crucial element in the design process.

In many current military aircraft, particularly single-crew aircraft, pilot workload levels are so high that they can limit the capability of the operational weapon system. It is easy to see how a diversity of projected scenarios, hostile environments, systems capabilities and task demands can all conspire to exacerbate the workload problem even further.

The addition of more capable systems and "pilot aids" can add to the already considerable problems if the underlying assumption is that the pilot can act as the all-embracing interface between all the disparate system elements. As the pilot reaches saturation level, he can become a limiting factor in the effectiveness and throughput of the weapon system.

Increasing the level of automation in systems functions has the potential to both enhance the aircraft's capability and to ameliorate the pilot workload problem. Automation of low-level housekeeping tasks frees the pilot to concentrate on being what he's best at: a high-level decision maker; whilst automation in the tactical areas of identification, analysis and attack heightens the performance of the man-machine combination in the very role for which it was procured. Identifying where and how much to automate is a crucial task. One of the most important elements in this work is tailoring the tasks that are demanded of the pilot so that they are suited to his unique capabilities.

It is thus apparent that the design of the total man-machine interface and the underlying systems as a coherent entity is possibly the most important task facing the prime systems contractor. This paper describes a structured design approach that aims to address these issues and illustrates how the method is being employed on the European Fighter Aircraft.

2 STRUCTURED TOP-DOWN METHODS

BAe has much experience in the use of structured top-down design methods for the analysis and design of complex systems. In particular, two specific design methods have been developed in-house to facilitate avionic and crew interface design.

- COntrolled Requirements Expression (CORE) has been developed as a tool to enable the decomposition of functional requirements into detailed systems design to be effected in a consistent and unambiguous manner. This approach has been used very effectively on the Experimental Aircraft Project (EAP) and is the basis for system design currently being used on EFA.

- In parallel with CORE, BAe has also developed a method of Mission Analysis to translate Operational Requirements into a statement of cockpit design requirements. These are expressed in terms of the desired level of systems automation and the pilot's need for information and controls within the cockpit.

Although the CORE and Mission Analysis methods have been derived independently, we now see benefit in integrating the two approaches. The cockpit and systems design tasks could now proceed from a common baseline and consistency of approach can be maintained at all levels of decomposition.

Further details of the CORE process as applied to systems design can be found in Reference 1. This paper will concentrate on the cockpit design process using Mission Analysis with an overview of the method being given in the following section.

Although BAe has been developing this analysis technique over several years, the exact form of its use on EFA was derived in collaboration with two of our partner companies Messerschmitt Bolkow Blohm (MBB) and AerItalia (AIT). In fact development of similar methods by MBB (Reference 2) and an AGARD working group (Reference 3) provides useful corroboration of the validity and merit of such an approach.

3 MISSION ANALYSIS METHOD OVERVIEW

The structured top-down approach starts with an aircraft Operational Requirement and works its logical way down to a detailed cockpit design. The following interim steps are generated as the process is pursued:

- A family of Mission Profiles is compiled;
- A typical Forcing Mission is chosen;
- This Forcing Mission is broken down into Phases of Flight;
- All relevant modes of operation per phase are identified;
- Each phase is divided into segments;
- Segments are described by a Task Listing;
- Functions Utilised are defined per Task;
- Automation Level is given per Function;
- Information and Control Function requirements are given for each Task.

The identified Functions Utilised and Automation Level then feed into the CORE process of detailed systems design. The Information and Control Function requirements are as yet implementation independent; this is where the Human Factors discipline is employed in translating the requirements into a detailed cockpit layout and moding philosophies that undergird the design.

Each step of the process will now be described in more detail.

3.1 Forcing Mission

The first step is to identify using the Operational Requirement a set of Mission Profiles that are representative of the uses to which the aircraft is expected to be put. As a considerable amount of effort would be required to break down every profile into a detailed task listing and replication of tasks would ensue, the concept of a Forcing Mission is postulated.

Out of all the Mission Profiles of a particular type (the Primary Profiles may be Air to Air) a single profile is selected as being forcing. This means that the one profile is used to drive out the majority of design elements that will also satisfy the other profiles. This Forcing Mission drives the design process as a first pass to establish a baseline cockpit layout and moding philosophy. In order that nothing significant is overlooked, any other key profiles can be given the same treatment as a check on the validity of the cockpit design that is taking shape.

3.2 Phases Modes and Segments

Each Mission Profile may then be split into a series of mission phases such as:

- Ground Procedures;
- Take Off;
- Navigation;
- Combat etc.

Each phase of flight can be identified to have several modes of operation, all of which pose different requirements on the cockpit design. For instance, Combat may be engaged in two different ways:

- Beyond Visual Range (BVR);
- Within Visual Range (WVR).

The BVR option is concerned with engagement of multiple targets at stand-off ranges and drives the requirement for correlation of information from all available sensors, detailed tactical analysis and planning.

The WVR option is a much more dynamic, rapid reaction task involving visual target acquisition and high-G manoeuvring to achieve sensor/missile lock-on and launch at large off-boresight angles.

In order that the task decomposition is split into manageable proportions, each phase is divided into segments. BVR Combat may constitute:

- Target Detection & Identification;
- Evaluation, Prioritisation & Decision;
- Pre-launch Manoeuvre;
- Launch Weapons;
- Post-launch Manoeuvre.

These segments define the level at which a detailed task breakdown can be generated.

3.3 Task Breakdown

Each distinct phase/segment (including mode variations) can then be split down into a list of discrete tasks that have to be carried out from start to finish of the phase. The major problem with the task breakdown appearing as a list is that the impression given is of the piloting task being very ordered, serial in nature and almost pre-ordained in sequence.

Whilst this may hold true for strongly procedural tasks such as ground procedures, in Combat for instance, life is anything but straightforward!

Tasks are re-scheduled or simply ignored as mission needs dictate, there being many occasions when the pilot would wish to do many things at one and the same time.

In order to represent more faithfully the true state of affairs, the tasks are divided into three categories:

- o **Primary Tasks**: These are the tasks that characterise each segment. They are mainly performed sequentially and in general require the pilot's foreground attention.

- o **Intermittent Tasks**: These are performed by the pilot as and when required or when the system working autonomously requests pilot intervention.

- o **Continuous Tasks**: These are performed continuously and concurrently, mainly monitoring tasks, preferably carried out by the systems which will alert the pilot only if required.

It is clear that this gross subdivision of tasks involves an initial suggestion of automation requirements, this is addressed in the next section.

3.4 Functions Used & Automation Categories

For each task, a function can be identified that is needed to carry out the task. These functions can vary from fully manual (pilot only) to fully automatic with degrees of blended co-operation in between. The categories of automation applied to the functions are:

1 **Manual**: purely visual, verbal or mental;
2 **Manual Augmented**: e.g. Fly-By-Wire;
3 **Manual Augmented - Automatically Limited**: e.g. Anti-skid braking;
4 **Automatic - Manually Limited**: e.g. Autopilot Attitude Hold mode;
5 **Automatic - Manual Sanction**: e.g. Target Nomination;
6 **Automatic Autonomous**: e.g. Systems Status Monitoring.

This requirement for automation from the operator's point of view will feed into the detailed systems design work which will be undertaken using CORE methods and tools.

3.5 Information & Control Requirements

For each task, the requirements for information presentation and control functions within the cockpit can be detailed. These requirements allow the pilot to either perform the task himself or monitor that the automatic systems are doing so satisfactorily.

This definition of the information and control requirements for the cockpit constitutes the prime output of the Mission Analysis. These elements can be further categorised dependent on the time required to access the information or control.

For instance, grouping the information and controls into three groups viz:

- o **Immediate Access Required**,
- o **Reasonable Access Required**,
- o **Non-critical Access Required**

is a great help in the layout and moding of the cockpit. Such categories when applied to information refer only to the data which is continuously available within aircraft systems. There is also data that is interruptive in nature and only arise following some trigger e.g. Data link messages or fault warning data. Three further categories are identified to cover these cases:

- o Immediate Presentation,
- o Immediate Alert (Reasonable access to information)
- o Alert Required (Non-critical access to information).

These control function and information presentation requirements as generated by the Mission Analysis are as yet independent of the means by which they will be met in the cockpit design. The above method is generic in the sense that it can be applied to any project. The implementation of these requirements is a very detailed and painstaking task which is project-specific and must embrace the areas of cockpit geometry, layout and moding.

These idealised requirements are also tempered by deliverable equipment performance, system design constraints, an evolving operational requirement and subsequent safety assessment. The following sections report on the unfolding and ongoing development of the cockpit design for the European Fighter Aircraft (EFA).

4 INFORMATION & CONTROL FUNCTION ALLOCATION

The cockpit requirements have been identified within mission phases upon selection of which the necessary information and controls to perform the task within that phase must be made available. Where the Mission Analysis has indicated a requirement for continuous availability throughout all phases of flight, then a dedicated presentation was considered in the cockpit layout; where the presentation could be governed by phase of flight, this was embraced in the overall cockpit moding task as follows.

4.1 Phase of Flight Moding

The phases of flight used in the Mission Analysis work were chosen to make that task more manageable. In the actual cockpit moding work, the guidelines applied in determining the actual mission phases used were:

- o the required phase shall be a major and complete sub-task of the mission;

- o the number of mission phases shall be kept to a minimum.

For the purpose of cockpit moding, the mission phases as derived in the analysis were rearranged and reduced in number thus:

- o Ground Procedures,
- o Take Off,
- o Navigation,
- o Combat (Air to Air),
- o Attack (Air to Surface),
- o Approach & Landing.

These were the phases of flight used in allocating the information and control functions to be either a dedicated presentation or function, or to be moded on one of the multi-function surfaces in the cockpit layout.
Normally a mission phase will be selected automatically as the result of a necessary event, e.g. Ground Procedures on power-up, Combat on weapon or radar air combat mode selection, Attack on selection of a weapon package and Approach and Landing on selection of the landing gear down.
However, where manual selection is required instead of automatic selection, the facility is provided for the pilot to engage the mission phase by a single action. All mission phases are selectable from any other mission phase (except Ground Procedures) and no selected phase will be changed by a power interrupt. Further such principles of cockpit moding are given in section 5.

4.2 Geometry & Layout

There are many factors that govern the geometry of any cockpit solution; some of which are directly under the influence of the cockpit designer, some are not. The external boundaries of the cockpit in terms of canopy, fuselage and pressure bulkheads are often influenced more strongly by aerodynamic, performance, structural and equipment installation considerations than by cockpit design principles.

The parameters which are defined in the cockpit design process are very much interactive and the final choice will of necessity be a compromise. For instance, an upright seat angle gives an increased view over the nose, greater depth of instrument panel and a more usable reach envelope; whilst a more reclined seating angle could give greater comfort and "g" tolerance.

A wide percentile range of pilot sizes has to be accommodated which sets bounds on reach and ejection envelopes. The tools available to the designer in setting the cockpit configuration now include computer modelling packages as well as the more traditional mannequins on drawing board and wooden mock-up.

Having fixed the cockpit geometry, the first level of the layout task is the allocation of crew information and control functions to:

- o Manual Data Entry,
- o Direct Voice Input,
- o Warning System,
- o Direct Voice Output,
- o Get You Home Instruments,
- o Hands On Throttle And Stick (HOTAS),
- o Dedicated System Controls & Indicators.

Next comes the task of allocating areas within the cockpit real estate to house these instruments, indicators and controls. These should all be arranged in accordance with the importance of the item, frequency of use and association of functions. To aid in this process, the controls on the side consoles can be remoted from the controlled equipment allowing a more ergonomic and hence optimum layout of control panels to be realised.

The layout is developed on the drawing board and using 3-D computer modelling techniques which leads to a full size white-on-black representation of the cockpit on a wall board. The human and computer impressions of the layout are amalgamated into a 3-D full size wooden mock-up of the cockpit which is used extensively for assessment of the designers' proposals using company and customer aircrew.

5 COCKPIT MODING

The aim of the cockpit moding is to provide the pilot with the information and control functions necessary to perform his tasks in the most effective manner. To this end the moding is concerned with how and when information from the aircraft systems is presented on the multi-function displays, helmet mounted display or the get-you-home instruments and how the pilot interacts with these sub-systems using direct voice input, the manual data entry facility, the HOTAS functions or the multi-function controls associated with the display surfaces. Failure situations on the aircraft and hazards external to the aircraft both need to be alerted to the pilot and how these can be integrated within an intelligent warning system is also a product of the cockpit moding.

The first step in this long and complex task is to establish the overall principles and ground rules as a framework within which the detailed moding must fit. These principles of cockpit moding cover several areas within the cockpit design process, the major elements of which will be considered in turn.

5.1 Automation

The automation requirements from the user point of view are developed from the Mission Analysis work and operational experience. Guidelines on how automated tasks should be integrated with the cockpit are given and also specific areas are identified where automation should be considered. This latter consideration has obvious implications for the system design task and therefore involves much iterative discussion with the system designers.

The categories of automation outlined in the Mission Analysis have been simplified so that there are three levels of control to be considered:

- o Manually controlled tasks shall be initiated by and involve the pilot using his judgement and mental or physical capabilities;

- o Semi-automatically controlled tasks shall generally involve co-operation between the pilot and a process. These tasks may require pilot mandate or sanction;

- o Automatically controlled tasks can carry on without pilot action.

5.2 Display Moding

The large amount of information and control functions which have to be managed via the multi-function display system cannot be displayed simultaneously. For the purpose of intelligibility and for clarity of presentation the information and control functions need partitioning. This is achieved by allocating information and control functions to mission phases and allowing a maximum of three levels of presentation:

- o **Default** - Immediate access required - defines the default level of information which will appear on selection of a mission phase;

- o **Level 1** - Reasonable access allowed - will be available from any level by a maximum of one selection either as information additional to the present format or as a new format;

- o **Level 2** - Non-critical access time - will be available from any level by not more than two selections either as information additional to the present format or as a new format.

The split between the three levels is a function of importance, priority and frequency of use of the information and control functions concerned. The limitation to three levels is chosen as a compromise between the desire not to clutter the display formats and not to require excessive time to access information. Although a maximum of three levels of information presentation is allowed, effort is being applied to minimise the number of implemented levels whilst obtaining the necessary clarity and intelligibility of the displayed information.

Each display format is defined as a set of information elements tailored for a specific purpose. Information elements can be added or removed. The number of display formats and the hierarchy of access is determined by:

- o the detailed allocation of information;
- o the requirements for access to levels.

The pilot interacts with this information via the HOTAS XY controller, via the multi-function controls which are arranged adjacent to the display surfaces or by using DVI. These control means serve various functions as follows:

- o to select formats;
- o to alter the existing information;
- o to add new information;
- o to make subsystem mode selections;
- o to show options.

Failure of one or more of the displays or associated controls will create a reversionary situation. A HUD failure will be compensated by flight information available on the MHDDs. A MHDD failure will be compensated by reallocation of formats to good displays; no format reconfiguration or combination is envisaged. Total loss of the main display suite results in use of the Get You Home displays.

5.3 Hands On Throttle And Stick (HOTAS)

The HOTAS concept allows improved pilot performance during phases of high workload or stress by providing functions where:

- o Immediate access is frequently required;
- o Immediate access is required during combat or high-G manoeuvres.

These functions are related to sensor control, weapons control, flight management and defensive aids. The operation of a HOTAS control provides immediate visual, aural or tactile feedback to the pilot.

5.4 Manual Data Entry Facility

This facility combines the data entry and moding tasks from a variety of aircraft subsystems into one focal area in the cockpit. Its five main functions are:

- o Subsystem selection keys dedicated to
  - Navigation (waypoints and routes),
  - V/UHF Radio 1 & 2 (modes & freqs.),
  - Data Link,
  - TACAN (modes and channels),
  - NIS / IFF (modes and codes),
  - Defensive Aids Subsystem,
  - Microwave Landing System,
  - Miscellaneous (IN & CW data);
- o Moding keys for task selection;
- o Data Entry Keyboard for alphanumerics;
- o Two-axis toggle switch for error correction and data sequencing;
- o Set Waypoint and Change Destination.

5.5 Direct Voice Input

DVI may be used where appropriate as an alternative and parallel moding and data entry medium for interaction with:

- o Manual Data Entry Facility;
- o Displays (HUD & MHDDs);
- o Autopilot;
- o Communications;
- o Mission phase moding.

Moding or data entry by DVI will have the same impact on subsystem functions as if a manual selection has been made such that the two interaction methods can be interchanged at any point in a routine. The feedback to DVI commands will always appear as for manual selections plus head-up feedback if implemented. The syntax of the vocabulary used by the pilot will be structured in order to balance flexibility with voice recognition success rate.

5.6 Warning System

Under normal operating conditions all onboard aircraft systems will be subject to automatic health monitoring through built-in test facilities. When practical, detection, diagnosis and correction of a fault will take place without pilot intervention. Each fault as it arises will be categorised and assigned a priority within that category according to the phase of flight and any other existing failures. The aim of the warning system is to:

- o **Alert** the pilot to a warning situation;
- o **Inform** the pilot what the situation is;
- o **Advise** the pilot of any consequences and action that should be taken.

To achieve this, four levels of warning category have been identified:

- o Category 1 - Procedural Warning;
- o Category 2 - Systems Warning: Red;
- o Category 3 - Systems warning: Amber;
- o Category 4 - Procedural Advice.

The main presentation and control of warnings information will utilise visual attention getters, attention getting sounds (attensons), the Voice Warning System, the Dedicated Warning Panel and the MHDD presentation of information relating to aircrew procedures and warning consequences. A Get You Home warning system is also provided for non-availability of the main warning system.

5.7 Get You Home Instruments

The reason for having Get You Home Instruments is to provide the pilot with an independent set of flight data which will enable him to return the aircraft to base in the event of total loss of the main display suite. Similarly, a number of "high category" warnings will be hard wired through to the Dedicated Warning Panel.

5.8 Helmet Mounted Sight

Both the highly manoeuvring environment of short range combat and agile weapons with large off-boresight capability make it essential that the pilot be able to engage in air combat without having to continually refer to the HUD for weapon aiming information. To this end, the HMS will be focused at a nominal infinity and be used mainly for Radar aiming/cueing of missiles and for autonomous HMS aiming where the missile is slaved to the sight.

5.9 Mission Data Loading

All mission-specific data recording and loading will be performed by means of a portable storage medium so that manual input of mission data by the pilot during Ground Procedures is avoided. Typical data to be loaded by this means includes:

- o Armaments package & configuration data;
- o Digital map data;
- o DVI voice templates;
- o Navigation waypoint & route data;
- o Tactical attack & defensive data;
- o Pilot Sensor Moding Key (PSMK).

This last item, the PSMK, is a very useful facility whereby the pilot can specify default values to certain attributes of the Displays and Controls sub-system in accordance with individual preference.

6 AIRCREW ASSESSMENTS

Aircrew have already been involved in the formative design process thus far. Their experience and ideas have been tapped as part of the generation of the concepts, philosophies and design proposals. At the stage where the design has firmed up sufficiently to allow spatially representative mock-ups of the cockpit and front fuselage to be built, aircrew assessment of these facilities becomes a vital interactive and iterative task.

Two forms of mock-up vehicle are commissioned, namely static and active cockpits. Use is also made of more generic prototyping facilities. These three facilities are used for different purposes, each is considered in turn.

6.1 Static Cockpit

This cockpit is a spatially accurate 3-dimensional wooden mock-up integral with a representation of the aircraft front fuselage. It is fitted with representative seat, rudder pedals, stick and throttle tops. In the first instance control areas may be represented by white on black pictures of the layout; these are soon replaced by the actual form of control.

Aircrew to be used in the assessments are drawn initially from the flight operations departments of the partner companies. Their anthropometric measurements are already known and if possible, a wide cross section of the full percentile range is used. Later on customer-nominated aircrew are used to progress and approve cockpit developments. All aircrew are fitted out in full operational clothing as relevant to the particular assessment, including gloves, helmets, respirators, immersion suits, Nuclear, Biological and Chemical gear and any other personal equipment as required.

With the seat adjusted to put the pilot at the correct design eye position and the full harness fitted, assessment of the cockpit internal features is made. The acceptability of the reach and vision envelopes to all general display and control areas in the cockpit is assessed to agree its overall configuration. A more detailed evaluation is also performed covering the necessity for and location of every single feature in the cockpit.

The pilots are fully briefed on the assessment objectives and procedures, including a technical overview of cockpit and system philosophies. A structured proforma is used to conduct each assessment and to elicit pilot opinion and rating of the particular features being assessed. Room is also allowed to glean any further comments and suggestions which the pilots may wish to make.

At the end of each assessment phase, all the results are collated by the cockpit group so that from the consensus of pilot opinion, recommendations can be made for changes to the next standard of cockpit layout. These cockpit group recommendations are put forward for agreement at a subsequent wash-up meeting to which all aircrew who participated in the assessment are invited to attend. In this iterative manner, the cockpit layout is developed and refined through agreed standards.

The foregoing has considered assessment of the cockpit internal characteristics; in like manner external aspects of the cockpit are assessed. This may use the same cockpit shell or another that is integral with the full-scale aircraft mock-up as appropriate. The cockpit is mounted at the correct height from the ground and the surrounding area is marked with a reference grid.

The external vision envelope is evaluated using the graduations on the ground and assessment made of any visual obscuration caused by external aircraft structure. This form of vehicle is also fitted with a ladder, hand holds and external stairways as appropriate for both normal and emergency ingress and egress checks to be performed. Seat pull-out and escape envelope checks are also performed at this time. Although not at present the responsibility of the cockpit group, these forms of mock-up are also used for assessment by design personnel concerned with access to aircraft equipment from the maintainability point of view. With the advent of MANPRINT, this latter form of evaluation is as important a part of designing for human interaction as is the cockpit design and evaluation task.

6.2 Active Cockpit

In a similar way to that in which the static cockpit is commissioned and used, at a slightly later stage in the cockpit design an active cockpit is brought on line. The internal dimensions of the cockpit and the equipment with which it is furnished are as representative as they can be in form, fit and function given that much of it is either off the shelf equipment or manufactured in-house. The cockpit is linked to an assessment control station and the computer facilities that house the simulation software.

The basic facility includes a linearised, six degree of freedom aerodynamic response model, which when interfaced with the outside world system and the inceptors in the cockpit, enables the pilot to fly the simulation and receive realistic visual cues. Provision of aircraft system models and interactive displays and controls allows pilot assessment of the cockpit via mission-capable simulation.

Aircrew used for assessments in the active cockpit are drawn from the same pool as performed the static cockpit assessments. Very similar procedures are used for briefing, conducting and reviewing evaluations in the active cockpit. It is vital that the aircrew provided for this iterative evaluation and development process are fully representative of the final end user of the aircraft in terms of relevant physical and mental attributes.

This form of active cockpit is now seen very much as a design tool in its own right. It is commissioned and used as early on in the project as possible providing much useful information on parameters and moding to be incorporated in the developing design. It also gives increased confidence on the acceptability of proposed concepts and thus provides a risk-reduction function, so important to the system developer in a fixed price contract. This vehicle is the prime means by which acceptable user-in-the-loop performance is demonstrated; this may be a contractual obligation in the era of MANPRINT.

6.3 Rapid Prototyping

As well as facilities that are specifically geared to one project, there are more generic tools that have wider application. One such tool is the Generic Rapid Prototyping Tool that has been developed in-house from commercially available equipment. The GRPT has been used on EFA in parallel with the whole-cockpit assessments to investigate certain aspects of the interface off-line; solutions that have particular merit are fed back into the active cockpit for final evaluation.

This approach has been used to prototype novel formats; to rework existing formats that have been found unacceptable; to investigate the interaction of tactical symbology with colour map background; and to optimise the control laws for a display cursor driven under HOTAS XY control. The tool allows rapid iterations of concepts as whole formats can be developed in days, changes handled in hours and thus complete assessments carried out in a few weeks.

The GRPT has been used to such good effect that it is being considered as an ideal means of capturing the requirement for a particular MMI at the earliest stages of a project. Customer involvement in this activity is essential so that early agreement on the form and feel of the interface can be obtained.

7 SAFETY ASSESSMENT

Whilst on the one hand the design of a fighter aircraft is optimised for war-time performance, on the other hand the issue of system safety is also a prime consideration especially for peace-time flying. There are complex tradeoffs to be performed in achieving acceptable levels of both parameters recognising that enhancement of one may compromise the other.

A relatively high proportion (40%) of catastrophic fast jet losses are attributed to pilot error. This appears to be a convenient catch-all for accidents caused by inadequate training or ill-defined operating procedures or bad design of the cockpit interface which exacerbated a problem in a high-stress situation. The insidious nature of system-induced pilot error is also worthy of close examination.

The issue of safety within the cockpit is therefore much more than mere consideration of the physical aspects of the MMI; well established procedures exist for performing hazard analyses on hardware and software functions. It is also more than reviewing the likelihood of aircrew error although this is difficult enough in itself. There is an overlap between the two areas where the Interaction of the Man with the Machine is more important than the Interface.

It is unrealistic to look for this interaction being error-free; but it is important that the required interaction is as error-tolerant as possible.

Safety assessment of this nature is in its infancy with no widely available methods or procedures for carrying it out. A method of hazard analysis and safety assessment for the cockpit has been derived for use on EFA which addresses the issues raised above.

In general the approach has been to take each information element and control function within the cockpit and consider the hazard that could occur if the pilot:

- o incorrectly selects the control;
- o inadvertently selects the control;
- o fails to select the control as required;

- o misreads a displayed item;
- o mistakes one item for another;
- o fails to see a displayed item.

For each of these eventualities a detailed knowledge of its impact on aircraft system operations is required to assign a severity to the prospective worst-case scenario. The way in which the function has been implemented in the cockpit design is next considered to give a qualitative probability that the error might occur. The hazard severity and risk assessment (frequency of occurrence) are then used to assign a safety risk level to the function.

Each function then has an assigned safety risk level of High (unacceptable), Moderate (acceptable, subject to review) or Low (acceptable without review) as appropriate. A detailed justification is given for the assignment of each safety risk level. If the safety risk is unacceptable then action must be taken to reduce the risk. This action will depend upon the nature of the error/failure but should consider:

- o Redesign;
- o Incorporate safety devices;
- o Incorporate warning devices;
- o Apply specific procedures or training.

The results of this cockpit safety assessment along with similar assessments of all the other systems on the aircraft feed into an overall aircraft system safety assessment where more global safety issues are addressed. The development and application of this semiformal method for safety assessment of the cockpit is very much "hot off the presses" and therefore still subject to review and improvement.

8 CONCLUSIONS

EFA will benefit greatly as a potent Weapon System from the structured approach taken to both cockpit and system design. By virtue of this approach and the harnessing of appropriate Human Factors expertise, methods and tools, the EFA cockpit will be a flexible workplace that allows efficient, reliable and safe human operation with a manageable pilot workload. In the light of current EFA experience, the following conclusions can also be drawn:

Optimisation of the weapon system design can only be realised if a common approach is taken to the interpretation and implementation of the customer requirement in all design areas. This is nowhere more important than in the integration of design approach to system and cockpit functions.

A structured approach to the design of an integrated vehicle that considers the hardware, software and human together as a system is vital in realising enhanced weapon system performance whilst managing the pilot workload problem.

Structured system design methods and mission analysis / task analysis methods must be knit together as part of an integrated toolset. BAe is committed to the development of an integrated design process that allows all the attendant benefits to be realised.

Typical cockpit design methods and tools have equal application to the design of every part of the aircraft with which there is human interaction. The application of cockpit-oriented Human Factors skills and experience to other aspects of system design is essential in fulfilling the requirements of initiatives such as MANPRINT.

9 ACKNOWLEDGEMENT

The author wishes to acknowledge that the work reported herein has been carried out by numerous representatives from the four EFA partner companies working within the Cockpit Group at BAe Warton.

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Discussion

QUESTION G.H. HUNT

How many "Forcing Missions" do you need to analyse to ensure that the resultant cockpit design is not specifically optimised to a limited range of operational roles?

REPLY

You need to limit the full analysis to only a few (3 or 4) "Forcing Missions" to contain the task to a reasonable level. It is then important to validate the resultant design by testing that design against other missions to satisfy the designer that the chosen "Forcing Missions" were, indeed, the most demanding tasks.

QUESTION M. JACOBSEN

Was the task of Eurofighter cockpit design shared by the 4 nations or was it the sole responsibility of B Ae?

REPLY

The 4 nations are involved in the cockpit design process and are represented on the cockpit assessment working group.

CVA, Cockpit
Design and Development Tool

by
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Summary

The conceptual design and development of a modern helicopter cockpit requires the consideration of ergonomic, operational and technical aspects. New and additional technologies lead to a steady increase of data and workload, so that an essential task is to obtain an optimum layout of the "Man-Machine-Interface" (MMI). For the performance of this task MoD has charged ESG to generate a national Cockpit Design Tool CVA and to operate it in parallel with the TIGER development. Due to the national character of the CVA those tasks are primarily handled which concern the specific German portion of the TIGER program, e.g. the control and display system of the digital map generator the helmet-mounted sight/display system the HF data link.

These complex systems, however, cannot be investigated separately due to the multiple reciprocal actions with the remaining display and control system, but have to be considered with the overall cockpit.

Thus the CVA is the reproduction of a functioning 1:1 cockpit of the PAH2 version of the Tiger and is operated in close cooperation with the future user (pilot). It is a closed-loop simulator which enables the checking of important areas of the MMI not only in theory, but mainly under practical conditions long before a prototype of the new helicopter exists.

1. Problem Situation

The conceptual design and development of new helicopters and thus of new modern cockpits always requires a symbiosis between most recent technology and man in the cockpit. In this connection the emphasis was placed on the technology and not on the crew which is directly involved with the operation of the system, by tasks like helicopter command and control and mission performance. Moreover the physical characteristics and the intellect of man have hardly changed as opposed to the technology so that man tends to become the weakest link in the "Man Machine System".

The primary objective must be today to relieve the crew in the cockpit. Thus the crew-system interface is an essential key for not exceeding the limits of psychical and physical crew stress also under extreme conditions such as

- Lowest flight
- Night missions
- Operation under extremely bad visibility conditions

The problem becomes even more obvious by fact that an enormous increase in data volumes as the result of new additional sensors and inclusion in command and control systems leads to a steady data quantity and workload increase, thus exceeding the limits of error free data processing by man.

The design and layout of a future cockpit like for the TIGER is influenced by ergonomic, operational and technical aspects, whereby an essential task is the optimum layout of the "Man-Machine-Interface" (MMI), i.e. to present to the crew in the cockpit,
at the right time,
in the right presentation,
the right information,

and to design the control structure,
uncomplicated,
uniform,
error tolerant.

An essential aspect in this connection which is to be considered is that the perfection of the control and display systems is not provided if nothing can be added, but if nothing can be taken away any more.

In order to be able to perform this task

MMI Optimization

for the future TIGER version PAH2 effectively and cost-efficient the experimental program

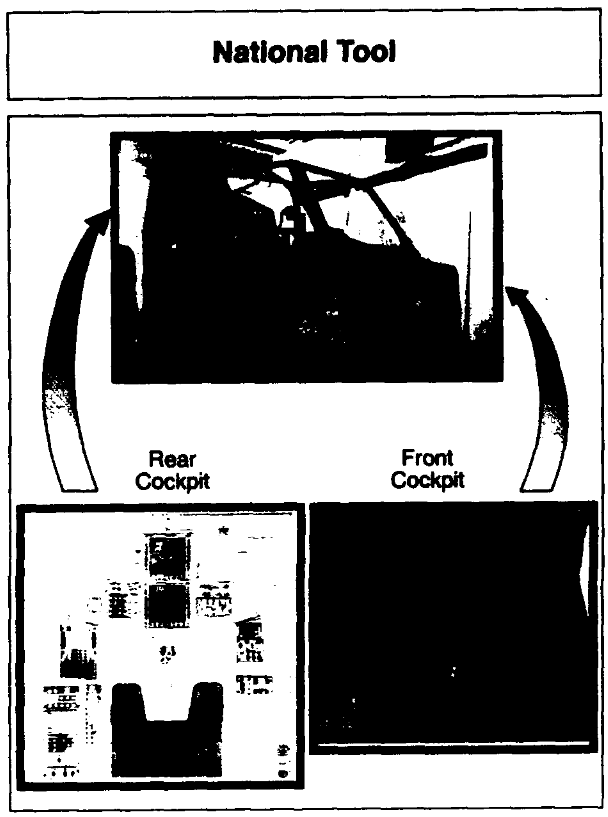

Figure 1: CVA a national Cockpit Design and Development Tool

CVA Cockpit-Versuchs-Aufbau

is performed in parallel with the development.

2. Tasks and Objectives

The CVA purpose is as follows:

- gaining experimental information on the man-machine-interface performance capability
- optimizing the development result, the development sequence with regard to time and cost aspects
- limiting the development risk

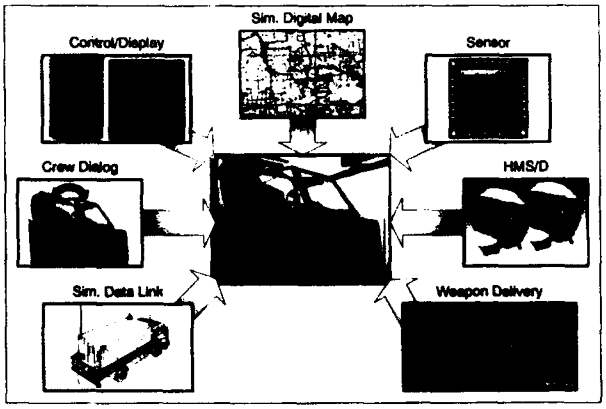

Figure 2: Main Tasks of the CVA

The essential task of the CVA design and development tool is the conversion of theoretical concepts to experimental hardware for investigating the MMI for the future TIGER under quasi-real operational conditions.

Thus the CVA comprises the following tasks:

- Specification of functions, control sequences, displays, arrangements, procedures etc. for the PAH2 cockpit due to information gained experimentally
- Checking of specified specifications and developments of the PAH2 cockpit
- Verification of theoretical proposals for control and display functions
  - o for crew communication in a tandem cockpit
  - o for workload relief in a tandem cockpit

In addition to ergonomic questions and requirements of a cockpit crew-supporting functions are tested experimentally taking into consideration new display and control technologies.

In order to enable a CVA to fullfil these objectives and tasks the experimental set-up must be flexible and modular with respect to hard- and software, in order to allow the rapid and economic investigation of alternative configurations resp. functions.

3. Approach

In order not to face the crew with additional demands as a result of the new technologies, but to enable the latter to place its demands on the future technologies involved, ESG practises a cockpit development approach which also considers the experience of the future users, the test pilots and flying instructors in due time.

Thus the CVA is an effective tool with which future users and system engineers can check, long before a prototype of a new helicopter exists, important areas on the MMI not only in theory, but mainly under practical conditions.

The strict realization of the conceptual guidelines

- modularity,
- rapid reconfiguration possibility,
- rapid modification capability,

have guaranteed that the CVA is ready for 11-12 experimental campaigns per year.

The CVA, of course, cannot and is not intended for replacing flight trials completely. It remains a fact that the degree of confidence in the results obtained by flight trials is higher than that obtained by results derived from a CVA, although flight trials are very time-consuming and expensive. With regard to the latter aspects, the obvious advantage is offered by a support tool like the CVA, as it enables the performance of the tests

- without flying authority
- irrespective of the weather conditions
- with non-flight-qualified cheap commercial equipment
- without consideration of environmental critical and flight safety critical aspects

For these reasons the CVA, as a link between the developing source and the user, is an important effective and cost-favourable design and development tool enabling the limitation of the risks associated with a complex cockpit development.

4. Description of the CVA

The CVA is a stationary duplicated full-scale fully functioning PAH2 cockpit, i.e. a tandem arrangement of the crew work stations with the respective control and display facilities, such as:

- Multi Function Displays (MFD)
- Helmet Mounted Sight/Display System (HMS/D)
- Control and Display Units (CDU)
- Radios Frequency Indicator (RFI)
- Weapon control elements
- Backup instruments

In addition to the actual cockpit setup the design and development tool CVA includes:

- A simulation facility for the not yet available original digital map unit
- A low-cost external vision unit
- A sensor vision facility
- A target generation facility
- A test engineer stand

For the control of the system efficient simulation computers, interface computers and symbol generators are used.

In the following the most important control and display elements are briefly described.

The primary control facilities cyclic stick, collective stick and pedals can be adjusted, like the seats, individually to the respective trial crew. Furthermore the control facilities between the front and rear cockpit can be influenced by a test engineer. Thus it is possible to investigate the crucial subject crew communication in a tandem cockpit.
The MFD's include flight control, navigation, position, weapon and system information, whereby this information can be displayed as a function of the mission,
- continuously,
- as required,
- automatically.

Due to the special mission conditions of the TIGER the simulation of the mission phase target acquisition, target engagement plays an essential part. In this phase the sensor information is displayed to the crew overlayed with synthetic symbology for flight control and weapon employment on the HMD.

The central Control and Display Unit (CDU) is located in the left front console area (front and rear cockpit).

It is the main input unit and is primarily used for controlling the following:
Flight Management Functions,
Communication,
Navigation,
Digital input of system data.

With the help of the Line Selector and Fix Function Keys information on the MFD's is added/cancelled as a function of the situation.

4.1 Facility for the Simulation of the Digital Map Unit

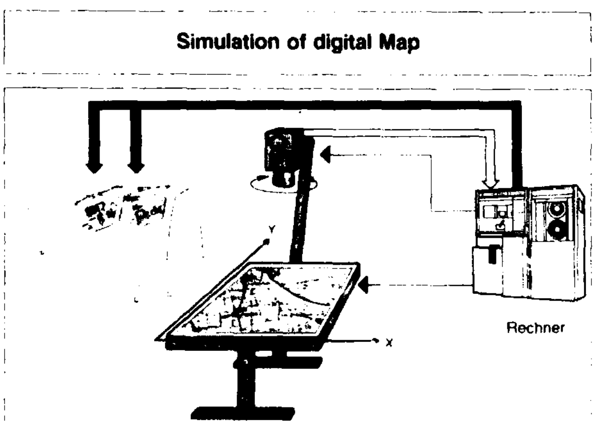

Figure 3: Simulation Facility for the digital Map

This facility enables the simulation of the functions of the future digital map unit which is required by the PAH2 on the displays for aerial navigation and display of the tactical situation. The controlling of the map takes place as a function of the location and heading of the helicopter.
The map scales 1 : 50 000, 1 : 100 000, 1 : 250 000, 1 : 500 000 and a zoom function are realized. On the actual map representation the information on the tactical situation, flightpath control, obstacles are superimposed. This information is summarized in so called thematic classes.

In addition to the actual map function the demanded Video Memory Function

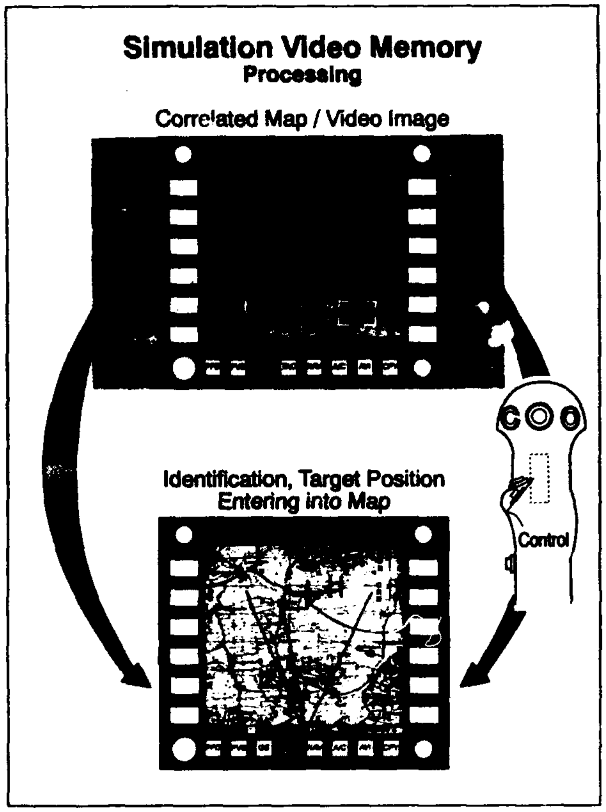

Figure 4: Video Memory Function

is simulated. It permits the evaluation of stored sensor video individual images resp. sequences (in cooperation with the sensor vision-target generation facility) and the take over of targets in the map representation.

4.2 Low-Cost External Vision

On the basis of digital terrain data a simple computer-generated external vision is generated which is adapted to the CVA objective. The term "simple" here refers to the degree of detail of the terrain representation. The low-cost external vision is used for flying from place A to B.

4.3 Sensor Vision Facility

The sensor vision facility consists of a landscape generator which generates on the basis of digitized landscape images reality-true synthetic computer pictures, as if a pilot or commander would see the landscape through his sensor. The degree of detail of the sensor vision is of very high photographic quality as opposed to the low-cost external vision. The field of view (FOV) available is as follows:

30 0 x 30,0
5,0 x 5,0
2,5 x 2,5

The pilot and commander can select between the FOV's indicated independently from each other, depending on the task.

Furthermore the representation as TV or TI image in different sensor picture qualities is possible, whereby the sensor picture quality can be varied online by the test engineer in charge. In accordance with the sensor arrangement (Mast/Bug mounted) of the TIGER two eyepoints are realized at an altitude difference of approximately 3 mtrs. The viewing directions of the pilot and commander are independent from each other, and are controlled by the respective line of sight of the HMS system, resp. by a joystick/Gunner Armament Grip (GAG).

The sensor vision facility is used in the course of target acquisition, identification, fighting, i.e. if the helicopter is hovering and the crew requires a detail-true external view.

4.4 Target Generation Facility

The target generator is used for the visual representation of targets so that - in combination with the landscape generator - the crew receives a realistic representation of the position area including ground and air targets. The system is designed such that up to four targets can be activated simultaneously and can be controlled by a test engineer. Thus a high flexibility is reached, in order to generate for the crew a practice-oriented workload. A suitable video switching facility enables the crew to switch the sensor image of the respective other crew remember to the own MFD.

4.5 Test Engineer Stand

The test engineer's stand is designed such that the following functions can be performed:

- Simulation of a ground radio station
- Control of the test sequences
- Supervision of the test sequences
- Stimulation of system functions

For that the test engineer has three MFD's, one RFI and a data input unit. Thus he is in a position to indicate for him one of the information presently shown in the cockpit (MFD1, MFD2 and HMD pilot/MFD4 and HMD commander) including the respectively current radio frequencies.

Furthermore the computer configuration, its performance capability and the modular functional setup offer adequate flexibility and growth potential for modifications and extensions.

5. CVA Functions

For the dynamic closed loop operation of the CVA all necessary functions

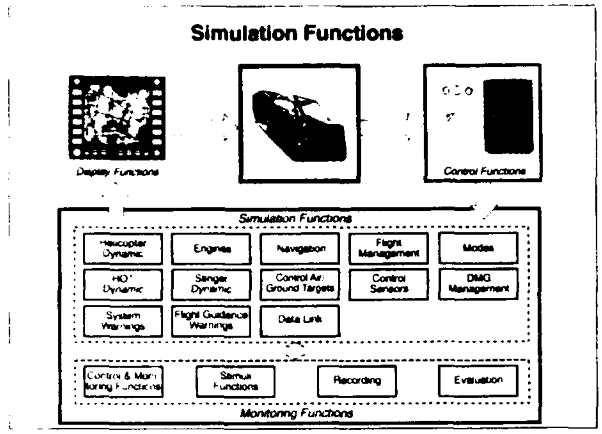

Figure 5: Overview of Simulation Function

were realized, whereby, due to the large number and complexity of these functions only a rough survey is given here.

The CVA functions include:

- Display functions
  Display and symbol generator functions
  Sensor vision
  External vision
  Optical warnings
  Acoustic warnings

- Control functions
  Helicopter control
  CDU-functions
  Weapon control
  Visionics
  Map unit control

- Weapon system-specific simulation functions, such as
  Helicopter dynamics
  Engine functions
  Navigation
  Flight management
  Mode management
  Weapon functions
  Map unit management
  Warning functions
  Data link

- Basic simulation functions, such as
  Test and control functions
  Stimuli functions
  Recording/evaluation functions

The necessary simulation functions are stimulated by the inputs of the crew (test engineer) and the respective information is shown on the display units in the cockpit, so that the test crew is part of the CVA closed loop simulation.

In the implementation of the functions attention was paid to modularity so that it is guaranteed to modify/reconfigure the system within short times.

6. Test Implementation

Since autumn 1990 the CVA has been used by the national users. In 1991 eleven one-week test campaigns on different subjects took place. For 1992 another eleven test campaigns are intended. In the further (at present booked out until 1995) future use

of the CVA program-oriented extensions and modifications are planned. In the following a short survey on the subjects handled so far in the CVA is provided.

The main areas of test are as follows:

1. Control structure and control functions of the digital map unit
2. Comparison of two different CDU control surfaces
3. Special symbologies for the HMD

To 1:
This complex work package concerns the control and display elements such as: MFD's, CDU, GAG, visionic panel, sticks. As essential tasks of the commander the following was/is dealt with:

Control sequences
Application of the thematic classes of the digital map unit
EDIT functions of the digital map unit
ZOOM functions of the digital map unit
Data link
Error messages of the system
Video memory management functions

In the course of the experiments with the pilots the weak points of the theoretical specifications were generated and as a result an optimized control and display alternative was presented, which meets the operational requirements.

To 2:
The subject of discussion was a CDU control surface with a single (smaller) and a double function keys (larger) keyboard.

The experimental investigations under participation of eleven pilots in a quasi-real environment were to prove with which one it was possible to enter faster and more error-free formatted text such as waypoints, frequencies and unformatted text such as free texts. The experiments took place with and without ABC-protective gloves and with and without additional workload of the operator. The evaluation clearly showed that the single keyboard despite smaller keys can be better operated also with ABC gloves.

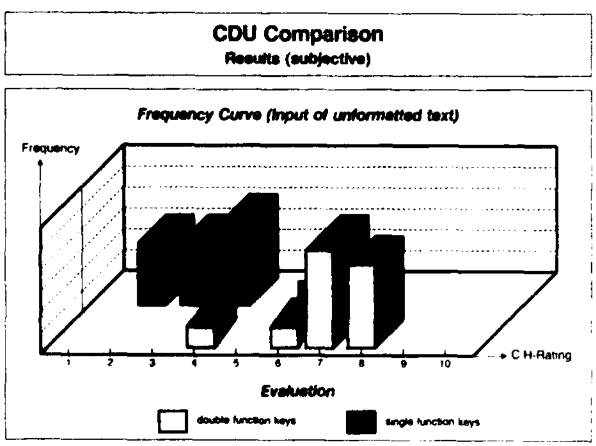

Figure 6: CDU-Keyboard Comparison

To 3:
The experiments on HMD symbology are presently performed in the CVA with a monocular HMD (FOV 30 x 40). The experiments are broken down acc. to:

- HMD-symbology for flight guidance
- HMD-symbology for weapon employment

At present the symbology for flight guidance is investigated. First results after two experimental campaigns have clearly shown that the theoretical specifications shows a strong overloading of the HMD symbology. Therefore alternatives were developed and tested with the pilots, for the purpose of a reduction of the most important aspects. Furthermore, like in the case of the MFD additional information can be added/cancelled as a function of the situation, whereby the HOCAS has to be considered here. Final results will be available in the course of 1992. It is intended to continue investigations with a binocular helmet system still in 1992.

The evaluation on 1 - 3 was performed:

- subjectively by questioning (Cooper/Harper-Rating) and collection
- objectively by the determination of control times and error frequencies.

Furthermore, if required, experts of the Flight Medical Institute in Manching were included in the investigations.

7. Conclusion

The design and development tool CVA permits, in close cooperation with the user, to specify experimentally the requirements of a modern tandem cockpit, to convert theoretical specifications and to verify them, and to guarantee the optimization of the control and display functions for work reduction, so that the following is guaranteed for the cockpit development:

- Adaptation of the technology to man
- Reduction of the control steps
- Integrated situation-adapted information representation
- Automatisation of routine tasks

MAN-MACHINE INTERFACE WITH SIMULATED AUTOMATIC TARGET RECOGNITION SYSTEMS

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1. SUMMARY

Growing numbers of targeting information sources in military cockpits have led to the development of automatic target recognition (ATR) systems. Since initially most ATRs will be used with an operator, a series of experiments was conducted to investigate aspects of the interface between the operator and the ATR. Two experiments are described which measured the speed and accuracy of ship identifications made by an operator using information from an imaging sensor and a simulated ATR. These measures were compared to performance of the unaided operator and to performance of the autonomous ATR. The accuracy of the ATR, the format of its output, and the quality and type of the sensor information was varied in the experiments. The results are discussed in terms of their implications for the design of the operator-ATR interface that will lead to satisfactory system performance.

2. INTRODUCTION

Ten years ago the Advisory Group for Aerospace Research and Development (AGARD) published the Proceedings of a conference on the *Human Factors Considerations in High Performance Aircraft* (Ref. 1). The 1982 conferees, noting the exponential growth in the number of cockpit displays and controls in combat aircraft, were seeking ways to control pilot workload. They saw multifunction controls and displays, new display technologies, increases in the capacity and speed of onboard computers, and the increasing use of automation as the principle means of benefiting from the available equipment and information. Many concluded that even more information and equipment could be included in future avionics suites if their designs were based on good human factors principles and good models of human cognitive abilities.

As predicted, additional sources of information which permit new mission capabilities have been developed for the military cockpit. For example, with new techniques and sensors we now envision attack at low altitudes and high speeds, in all weather and lighting conditions. However the same problems apparent in 1982 still exist today: operator workload is too heavy to make optimal use of all of this information and equipment.

Workload problems are especially great during the targeting phase of the mission which extends from target detection to weapon release. During targeting, when the aircrew really needs to have all of the information available, a major concern is whether the crew members will have sufficient attentional and mental reserves to use information from these additional sources effectively. Thus the dilemma discussed in 1982 remains. On the one side, information is provided to allow the expansion of mission capabilities. On the other side, the operator is already too busy to use it optimally. As was the case ten years ago, new, more sophisticated automated systems are proposed as solutions. Some of these systems will take over the aircrew's routine operating and monitoring tasks. Others will assist the pilot in processing and integrating information and sensor data from multiple sources. Still others will vary the degree of automation to accommodate variations in workload.

2.1 Background

Many attempts are underway to develop automated systems that process and fuse targeting information. These systems are generally known as Automatic Target Recognizers (ATRs), whether they are designed to identify, to detect, to track a target, or to do all three. In fact, the design goals of different ATRs vary tremendously. Some are meant to carry out the entire range of targeting tasks from detection to weapon release without operator involvement. Others are more limited in scope, designed to do only one of the targeting functions, e.g., detection or identification. ATRs also vary in the nature and amount of the information they are designed to process and use. Some ATRs use information from only one sensor or information source. Others use information from several diverse sources, fused at some point in the processing.

Ultimately fully autonomous ATRs are anticipated that perform all aspects of targeting from detection to weapon release, without a human operator. However, most systems under current development are not yet robust enough to operate autonomously under all field conditions. ATRs that detect well also produce many false alarms; systems that classify or identify make many mistakes when they are operated in field conditions outside the laboratory. ATRs that work well in one type of terrain or atmospheric condition may not work well in another. For at least the next few

years, ATRs are going to need a human operator who can verify the output of the ATR, who can choose among alternatives reported by the ATR, or who can direct the ATR to process or reprocess sensor data of interest.

For now, ATRs can be viewed as operator decision support systems: systems that provide recommendations to the pilot, who retains the responsibility and authority for making the targeting decisions. Viewed as a decision support system, the ATR becomes another source of information in the avionics suite for the pilot. Its output must be accepted or rejected according to its correspondence with information from other available sources.

2.2 Operator-ATR Interface Issues

If an ATR implies "aided" target recognition, then the interface between the operator and the ATR is important to the ease with which the ATR recommendations are utilized and resolved with other information. The first element that must be considered in this interface is the nature of the ATR itself and of its output. In a recent survey of aircrew opinions about ATRs (Ref. 2), pilots report that, in addition to the ATR recommendation, they want to know what sources of information the ATR has used to make each of its recommendations. They also want available at all times a figure of merit (FOM), or quantity that expresses the probable accuracy of each recommendation.

Since the users want more than just minimal output from an ATR, it is important to examine the function and quality of the ATR, the nature of its FOM, and the display format for this information. What will be the effect of providing all of this ATR information on the accuracy and timeliness of targeting decisions? Will pilots be able to resolve conflicts that may arise when the ATR reports "cruiser" while the Forward Looking Infrared (FLIR) imagery shows a good picture of a frigate?

The nature and quality of other information available to the operator is also important, as is its correspondence to the ATR output. The operator must use this adjunct information to confirm or reject the ATR recommendations. Thus the quality of adjunct information may affect the overall targeting performance of the operator using an ATR.

In considering the operator and ATR performing as a system, it is of great importance to know whether the information that is available to the operator was also used by the ATR. If both are using the same or similar information, then their judgements will not be truly independent of each other, and both may be based on information of similar quality. If the operator is using different information than that used by the ATR, one of the two may be using more higher quality, less ambiguous information than the other. The operator-ATR interface should reflect these variations and assist the operator to weight both the ATR output and his own judgement as a function of the quality and independence of the information available to each source.

The decision making characteristics of the operator must also be reflected in the man-machine interface. Targeting decisions are made under time constraints and under stress. A good interface should mitigate operator errors. When ATR output disagrees with other information sources such as sensor data or sensor imagery, operators must resolve these differences by integrating several probabilistic and uncertain alternatives. When combining probabilistic information, humans typically perform in a sub-optimal manner.

Human decision making also is influenced by systematic biases. Anchoring is just one of several such biases that might affect targeting decisions made by an aircrew using an ATR. Anchoring in this context means that in a situation where the operator must choose between conflicting alternatives, he would be unduly influenced by the information source that he first considers. The operator who first notes the ATR output would most likely concur with the ATR; the operator who first notes a cockpit imaging sensor would most likely follow his initial interpretation of that image.

An adequate investigation of the interface between an operator and an ATR must include: (1) consideration of the nature of the ATR output, (2) the ATR display format and accuracy, (3) the additional information sources available to the operator, along with their quality and relationship to the ATR input, and (4) the decision making characteristics of the operator. All of these factors are parameters of the interface between the operator and the ATR and must be considered, varied, or controlled in an evaluation of the operator-ATR interface. To date there has been little research on this interface. The remainder of this paper describes the design and outcome of experiments conducted recently to learn about the operator-ATR interface.

3. EXPERIMENT 1

3.1 Method and Design

An initial study (Ref. 3) compared the accuracy and response times (RT) of an operator using a simulated ATR to identify* images of ships presented under time constraints with the accuracy and speed of an unaided operator in the same situation. This experiment replicated portions of an earlier study (Ref. 4). Operators were provided with FLIR imagery of ships in conjunction with the output of a simulated ATR. The subjects' performance in identifying the ships when aided by an ATR was compared to their unaided performance.

*The terms "recognition" and "identification" in this report are used interchangeably and refer to the subjects' ability to provide the correct name for a given image from the set of images.

The FLIR imagery showed a white-hot broadside image of a single ship taken from a set of seven ships. The FLIR images of each of the seven ships were shown at three different distances: near (5-7 kilometers (km)) which showed very clear, good imagery; medium (11-13 km) which gave fair imagery; and far (16-18 km) which was very poor, blurred imagery.

Three simulated ATRs were used which differed from each other in the accuracy of the ship identifications that they made. The most accurate was correct 90% of the time, the next was correct 70% of the time, and the poorest was correct only 50% of the time. In all cases the output of the ATR was the name of one of the seven ships and a figure of merit (50, 70, or 90) which expressed the overall accuracy of the ATR. No information was provided to the operators on how the ATRs obtained their output, but in all cases the quality of the ATR output was independent of the quality of the FLIR imagery shown to the operators. Thus even when the FLIR showed very poor, blurry imagery, the 90% ATR was still correct 90% of the time. Conversely, when the FLIR was excellent, the 50% ATR was correct only half of the time.

The FLIR imagery and ATR recommendations were presented for 2, 4, 6, or 8 seconds. Subjects could take longer to identify the ships, however they could not study the imagery or the ATR recommendation for longer than the time specified in the experimental design. They were told that while accuracy was more important than speed, they should make their identification decisions as quickly as possible.

Sixteen subjects participated in the experiment. All subjects were pre-trained to familiarize them with the seven ships, and were familiarized with the experimental conditions.

3.2. Results for Accuracy of Identification

3.2.1 *Aided Versus Unaided Performance*
The results showed that an operator was significantly more accurate in identifying the ships when aided by an ATR than he was when unaided. Fig. 1 shows the percentage of correct identifications for the unaided operator and for the operator aided by the three ATRs. Percentages of correct identifications increased both as the reliability of the ATR increased, and also as the quality of the imagery increased ($F(3,45) = 21.52$, $p < 0.001$ and $F(2,30) = 49.27$, $p < 0.001$, respectively). Fig. 2 shows the difference scores between aided operator performance for each of the ATRs and unaided operator performance: difference scores above the zero line mean that the performance of the operator using an ATR was better than the unaided operator performance, while those below the zero line indicate the opposite.

Fig. 2 shows that in almost every case the aided performance was substantially better than the unaided. Gains exceeding 15% were found when operators were aided by reliable ATRs and when they had imagery of 13 km or closer. Even the very poor 50% ATR, when used by an operator with good or even fair imagery, produced gains between 4% and 10%. Contrasts showed that all of these gains in percentage of correct identification were significant except the overall difference (ignoring image quality) between unaided performance and performance aided with ATR FOM 50.

3.2.2 *Aided Versus Autonomous ATR Performance*
To compare aided operator performance to the performance of the ATR alone, difference scores were computed by subtracting the percentages of correct identifications made by each ATR acting autonomously from the percentage of correct identifications made by the operator using that ATR. Fig. 3 shows these difference scores.

As before, positive difference scores indicate that the performance of the operator using the ATR was better than the autonomous ATR, while negative scores indicate the opposite. The difference scores were not different from zero when averaged over all conditions, but it is clear that there was tremendous variation in both the magnitude and direction of the scores depending on the ATR FOM and the FLIR imagery ($F(2,30) = 14.88$, $p < 0.001$; and $F(2,30) = 22.43$, $p < 0.001$, respectively).

An operator using the 90% ATR was less accurate than the autonomous 90% ATR, as shown by the negative difference scores, while an operator using the 50% ATR was almost always more accurate than the autonomous 50% ATR. Contrasts showed that both of these differences were significant.

Operators using the 70% ATR were sometimes better and sometimes worse than the ATR alone, depending on the imagery. On the average, the contrasts showed that there was no significant difference between the operator using the 70% ATR and the autonomous 70% ATR.

An analysis of operator compliance with the recommendations provided by the ATRs showed that operators tended to comply more with the more reliable ATRs, and that their degree of compliance was not dependent on the quality of the imagery. Analysis also showed that, when operators disagreed with the 90% ATR, they almost always were incorrect. When they disagreed with the less reliable ATRs they were able to improve overall performance.

3.2.3 *Time-Limited Information Presentation*
Identification accuracy did not vary as a function of whether the information and imagery was presented for 2, 4, 6, or 8 seconds. These results are shown in Fig. 4. Although some subjects reported that they would have liked more time in the 2 second condition, apparently that was sufficient time to identify the ships and use the ATR information.

3.3 Results for Response Time

RTs increased directly with exposure time ($F(3,43) = 24.69$, $p < 0.001$). It is not surprising that subjects

who had more time to look at the imagery took longer to respond. These results are shown in Fig. 5.

In the RT analyses it is interesting that the variation in RT as a function of the degree of aid was marginally significant ($F(3,42) = 2.41$, $p < 0.08$). Fig. 6 shows that the operator use of a highly reliable (90%) ATR took less time than the unaided decision, but operator use of the less reliable (50%) ATR took longer. It takes an operator time to use an unreliable ATR; the operator can work faster unaided. Only good, reliable ATRs save operator time. Contrasts show that the RT associated with the operator using the ATR with FOM 90 was significantly shorter than the RT associated with the use of the ATR FOM 50 ($F(1,14) = 11.56$, $p < 0.004$).

There were no other significant main effects or interactions in the RT analyses. RT did not vary with image quality of the FLIR. This indicates that the operators did not spend a longer time in making their identification decisions when they had to base their decisions on poor imagery viewed for limited, fixed amounts of time.

These results are very similar to the results found in an earlier experiment with two exceptions (Ref. 4). First, the current subjects performed slightly less well in almost every condition. Possibly this performance decrement was a trade off of speed for accuracy since in the earlier experiment there were no time constraints, and subjects frequently spent the greater part of a minute examining the imagery. Second, in the earlier experiment, unlike this one, operators using the 70% ATR were consistently better than the autonomous 70% ATR, regardless of the imagery presented. Other differences between the results of the two investigations were minor, or could be traced to the differences just noted.

3.4 Discussion

These results have major design implications for the operator-ATR interface. Operator performance will vary both with the level of accuracy of the ATR and the quality of the imagery that the operator has to work with. Because all of the comparisons showed that aided performance was superior to unaided, it is evident that performance of the overall system will be maximized by using an ATR even if it is a very poor one, at least within the ATR performance ranges that were tested.

Further research is needed to examine whether ATRs that are less accurate than 50% will also enhance operator targeting decisions. There may be a lower limit of accuracy for an ATR where the operators' performance will no longer be enhanced by having ATR information available. Another experiment (Ref. 5) has shown that operators using two sources of imaging information are unable to ignore poor quality information. They integrate poor and good information, consequently doing less well than they would have done had they based their decision on only one good information source.

The results of this experiment also imply that an ATR that is as good as the simulated 90% ATR should be used as an autonomous system. The operators did not improve on the performance of the autonomous 90% ATR, regardless of the quality of the imagery that the operator was shown.

It is also clear that the 50% ATR should not be used as an autonomous system, rather it should be used with an operator. The performance of operators using the 50% ATR was always equal to or better than the autonomous 50% ATR, and also always better than or equal to unaided performance. In fact, with good imagery (imagery of objects closer than 13 km) the operator-50% ATR performance was synergistic. That is, the system performance was superior to the performance of either component measured by itself. This synergism was also seen in the prior experiment (Ref. 4) for operators using both the 50% and 70% ATRs.

The design implications of performance using the 70% ATR are less clear. If the operator has good imagery (closer than 13 km) plus the 70% ATR output, performance is equal to or superior than that of the autonomous ATR or of the unaided operator. Performance was not always synergistic, but it was always at least equal to the performance of the component parts. With poor imagery however the performance of the operator using the 70% ATR was poorer than that of the autonomous ATR. This suggests that, if this ATR were to be implemented for use, the ATR should be used with an operator, but the operator should not be shown poor imagery.

4. EXPERIMENT 2

4.1 Method and Design

In the second set of experiments, the same incoming imaging information was provided to both the ATR and the operator. The operator saw an image of a ship, and the ATR, using the same type of imagery, produced an identification of the ship.

The imagery was simulated. To create the basic, undistorted set of simulated imagery, 15 images of ships, taken from *Jane's Fighting Ships* (Ref. 6), were constructed by representing broadside views of each ship by 60 vertical bars. Each basic undistorted ship looked like a sort of histogram (see Fig. 7 for an example). These fifteen ideal ship images were given to the operators in hard copy, and in addition were stored in the computer as a reference library set to be used by the ATR for comparison with incoming imagery.

The simulated incoming imagery was constructed in the same way as the ideal basic set, but to represent sensor and environmental noise, each vertical bar of each image was perturbed vertically by adding or subtracting values randomly selected from a normal distribution with a mean of zero and a standard deviation varied according to the amount of distortion required in the experiment. Image quality could be varied by perturbing each of the 60 bars which

constituted the image. This, in turn, caused variations in the accuracy of the operator performance and the accuracy of the ATR performance.

As in the earlier experiment, this experiment used two distortion conditions. The standard deviations of the perturbation distributions were selected based on pretests so that unaided operator performance and autonomous ATR performance would be roughly equal, and so that performance under High Distortion would be about 40% and under Low Distortion would be about 80%. (In the experiment these percentages actually were 40 and 41% respectively for the operator and ATR in the High Distortion condition, and 85% for the ATR and 54% for the operator in the Low Distortion condition).

The recommendation from the ATR was presented in several different formats. First, the number of recommendations from the ATR was varied in two ways by giving either the single, best recommendation, or by reporting the best five matches of the incoming imagery to the stored library images. Second, the FOM was presented in three ways: quantitatively (a number from 0 to 100); qualitatively (an adjective, such as "High", "Medium", "Low", or "Poor"), or not given at all. An unaided condition also was used as a control.

Overall, ATR recommendations were presented in six different formats in two distortion conditions to operators who identified 15 ships using the ATR recommendations along with simulated imagery. A seventh control condition determined unaided operator performance in identification of these same ship images. Altogether a total of 28 subjects from two different populations were tested at two separate times using this design.

4.2 Results

Analyses of the results of this experiment are still underway. Only a few significant findings, common to both populations that were sampled in the experiment, are highlighted here. Operators using an ATR performed significantly more accurately than they performed unaided, in both the High and Low Distortion conditions. Unaided performance in the Low Distortion condition averaged 54% for the two samples, while aided performance averaged 83%. Comparable figures in the High Distortion condition averaged 39.7% and 53.4%. Performance in the High Distortion condition was synergistic: the 53% accuracy of the operator using the ATR was also significantly superior to that of the autonomous ATR at 40%. There was no synergism in the Low Distortion condition: the operator-ATR system performed at 83%, which was not significantly different than the autonomous ATR performance of 85%.

Aiding reduced RTs in the Low Distortion condition from an average of 15.0 seconds to 11.5 seconds for the two experiments. In the High Distortion condition, however, aided RTs were not shorter than unaided RTs (respectively 17.4 seconds and 16.9 seconds).

Analyses of the Number of Recommendations and the FOM Format conditions showed in both samples that neither factor was significantly related to performance accuracy in the High Distortion condition. In the Low Distortion condition, however, accuracy of performance varied significantly as a function of these conditions.

Two kinds of display formats resulted in the most accurate performance. One of these provided five recommendations along with a quantitative FOM display; subjects were correct 72% of the time. The other gave one recommendation and a qualitative FOM; subjects were correct over 70% of the time.

The format that gave five recommendations with No FOM resulted in the worst performance with only 63% correct identifications. Also RTs increased significantly as a function of the number of recommendations and generally responses took approximately 2 seconds longer when the ATR gave five recommendations rather than one.

4.3 Discussion

The full implications of these findings for design must await a complete analysis. However it is clear at this time that ATR display design will affect the overall performance accuracy of the operator who uses it. The presentation of more information from an ATR (such as a larger number of alternative identifications or the presentation of FOMs) does not improve performance in all cases, and it may increase the response time.

The significant interaction between the display treatments and distortion level may indicate that the optimum display format will vary depending on either the absolute quality of the ATR, or on the quality of the ATR relative to the performance of the operator. With an ATR performing about equal to the operator at fairly low 40% levels, format does not greatly affect accuracy. A format providing the single best choice from the ATR, given without a FOM, would yield the most rapid response and presumably would yield a performance as accurate as with any other format. Given an ATR that is accurate more than 80% of the time, one that is about 30% better than the operator, the optimum format might well be the five best matches to the library images. However, this is true only if quantitative FOMs can also be provided and longer response times can be tolerated. Otherwise, display of five recommendations is a poor choice, according to these preliminary analyses.

In this study, optimum performance was obtained from various combinations of operator and ATR components. With the very good performance of the ATR in the Low Distortion condition, the presence of the operator did not improve or degrade the accuracy of the system. The ATR could act autonomously or not, based perhaps on the workload imposed upon the operator by other flight duties. However, with poorer

imagery, the operator's interaction with the ATR was required for optimum performance. In fact, the operator using the ATR produced a synergistic increase in performance.

5. CONCLUSIONS

Further experimentation is required to establish guidelines for optimum interfaces between operators and ATRs. The two experiments discussed here clearly demonstrate that the interface should be varied as a function of the accuracy of the ATR, perhaps measured relative to operator performance. Adjustments to the interface could potentially be made dynamically, with the degree of autonomy for both the operator and the ATR adapted as a function of the relative performance of each, the quality of incoming information, and concomitant workload.

The experiments also show that the format used to display ATR information can be adjusted to optimize performance. Further experiments are underway to define additional parameters which will optimize operator-ATR performance and which will additionally clarify the multiple relationships between the target, the sensor(s), the ATR, the display, the operator, and the decision making strategy.

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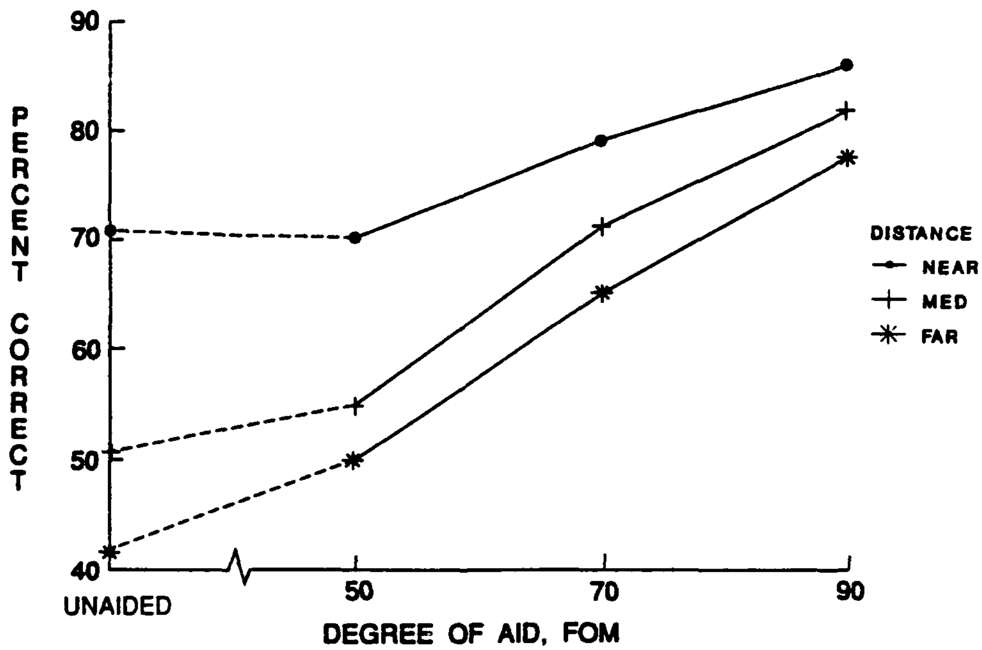

Fig. 1. Identification Accuracy as a Function of the Interaction of Degree of Aid and Distance.

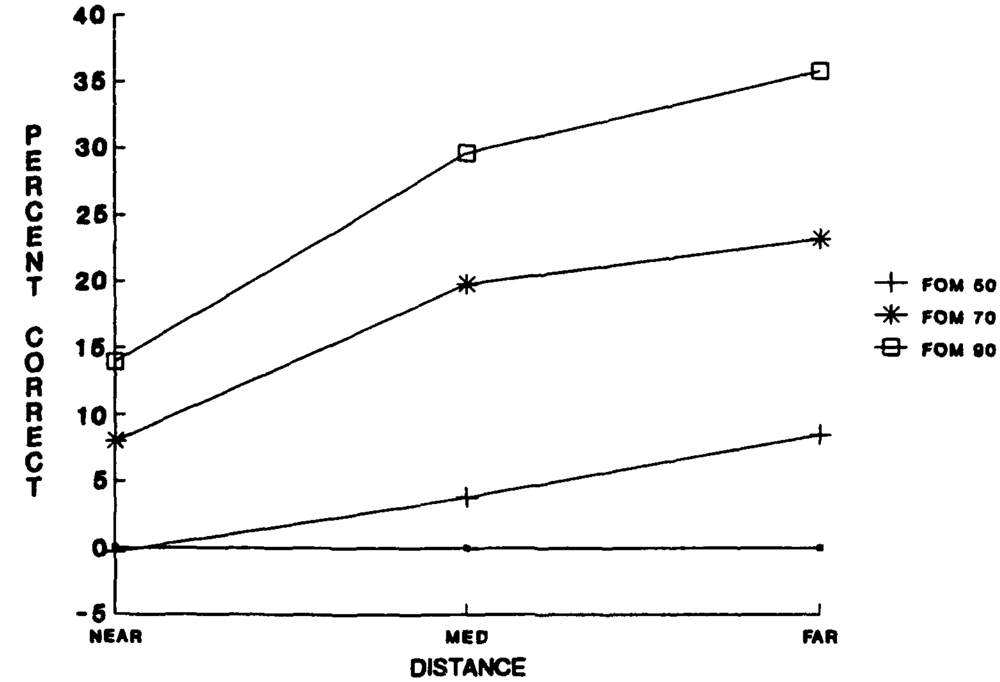

Fig. 2. Aided Minus Unaided Performance as a Function of FOM and Distance.

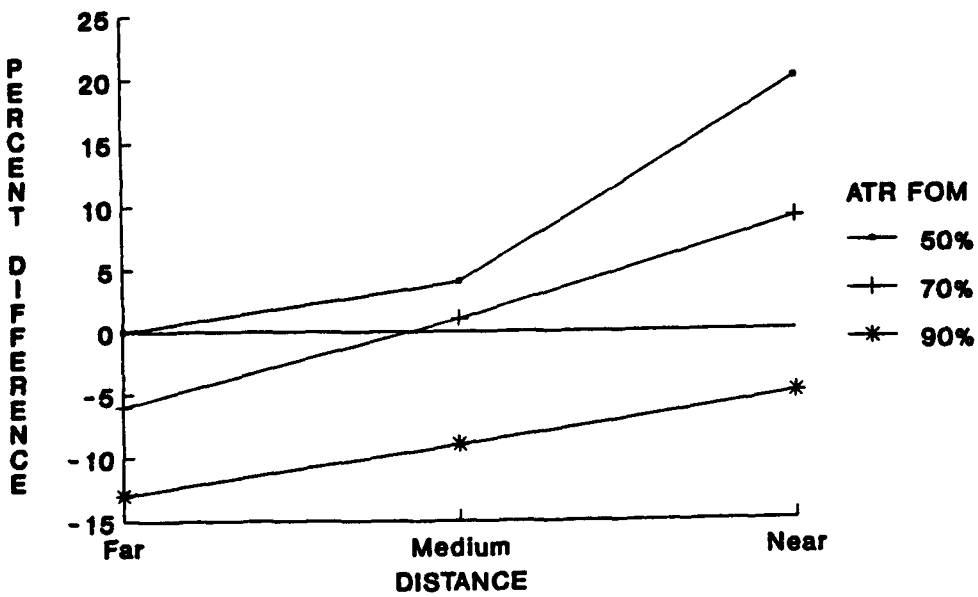

Fig. 3. Operator/ATR Performance Versus ATR Alone.

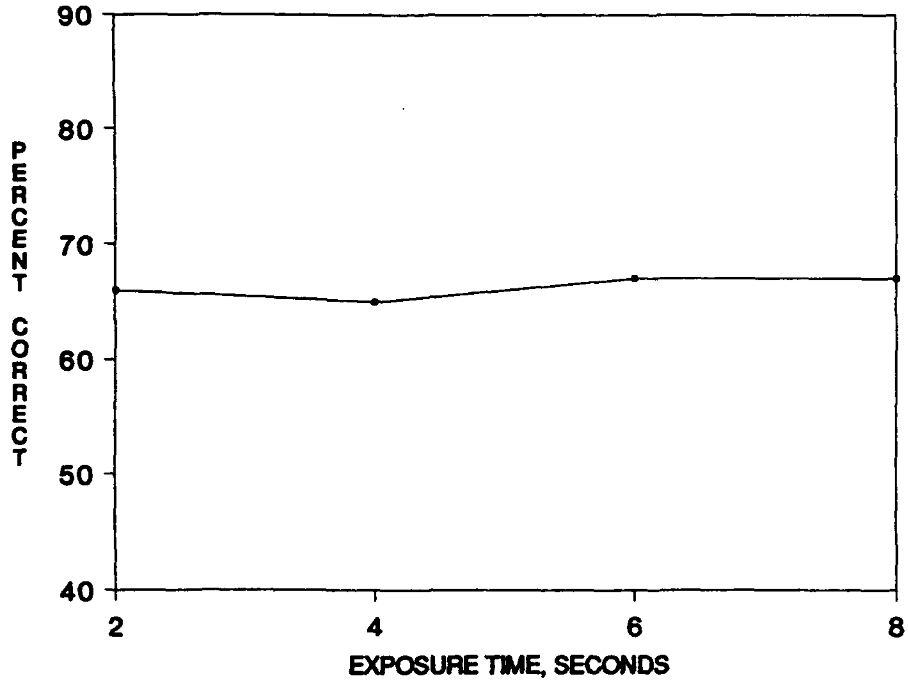

Fig. 4. Identification Accuracy as a Function of Exposure Time.

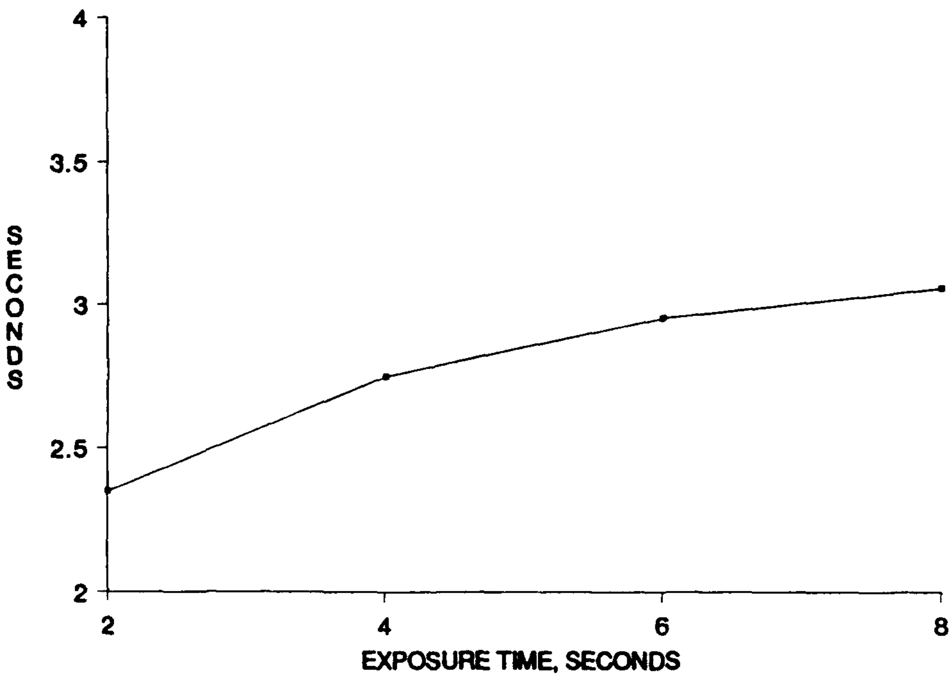

Fig. 5. Response Time as a Function of Exposure.

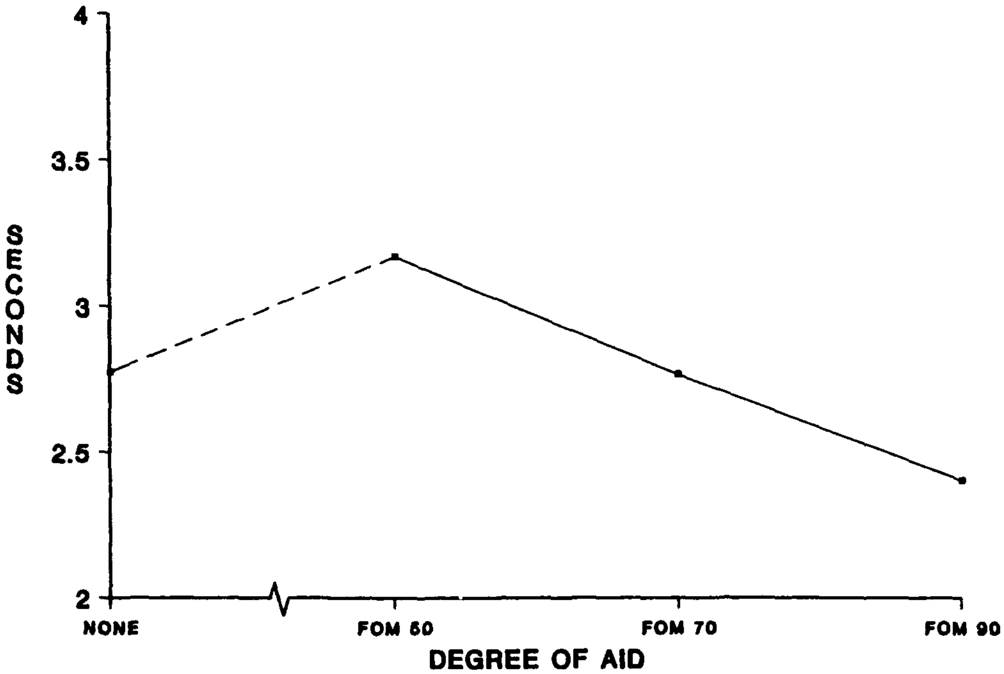

Fig. 6. Response Time as a Function of Aid Level.

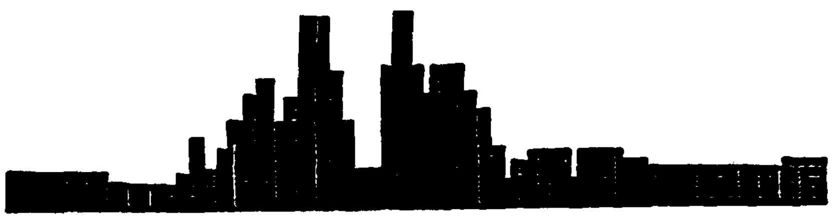

Fig. 7. CGN-36, the *California*, a Sample of the Simulated Imagery Used in Experiment 2.

Discussion

QUESTION E.J. LOVESEY

Did you use pilots for your trials? Was there an additional task (e.g. flying) other than the recognition task?

REPLY

Our subjects were scientists and engineers employed at NWC. On other, similar, target recognition experiments we have used pilots as well and have not found any systematic differences between them and the non-pilots in terms of the accuracy of their identifications.

We did not use a secondary task. We felt that the secondary tasks generally used did not properly represent the kinds of tasks that occur during the targeting phase of a mission.

THE ACTIVE-MATRIX LC HEAD-DOWN DISPLAY (AM-LCD) - OPERATIONAL EXPERIENCE AND GROWTH POTENTIAL

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Summary

After a protracted development period, the active-matrix addressed liquid crystal light valve is finding increasing employment in a variety of head-down primary flight instrument applications. Whilst the packaging efficiencies of such a flat panel technology are self-evident, many of its other attributes are also likely to have a profound impact upon crew station design. In order to successfully exploit the positive aspects of this technology it is appropriate that the avionics systems architects benefit from the, albeit limited, current operational data base and develop a realistic understanding as to the limits and rate of advancement pertinent to this class of display device. The following paper is offered as an element in this information dissemination process from a source that has maintained a presence in the technology since 1984 and has participated in AM-LCD solutions for such diverse air-vehicle requirements as YF-23, LH, P-3C and C-130

The content comprises:

(a) A cursory understanding of fundamentals.

(b) An overview of nature and extent of current operational examples of this technology as known in the public domain.

(c) An outline of specific primary flight instrument usage based upon a rigorous C-130 flight test program.

(d) A discussion of areas of ongoing research and advancement in terms of:

(i) Growth in display area/resolution/ modulation depths.

(ii) Centralized and distributed processor architectures.

(iii) Photometric efficiency via novel colour generation and lighting methods.

iv) Incorporation of autostereoscopic features resultant from the discrete pixel structures of the light valve device.

1. The Concept

The multiplexed, matrix-addressable liquid-crystal (LC) cell operated in a transmissive (back-lit) made has offered itself as a potential alternative to CRT devices in a variety of display applications for some considerable period. Despite spectacular advances in the non-linear electro-optic properties of the basic mesomorphs and similar sophistication in cell structures, the multiplexing level for simple cell structures has not approached the level satisfactory for large area, high information content/video capable displays suitable for the airborne environment. This restriction in performance of simple LC structures has been well covered in prior works and continues to be a focus of effort at the basic materials/process level as evidenced by advanced nematic eutectics, super-birefringent structures and the optically bi-stable ferro-electrics. Notwithstanding, the Display Industry has sought a more direct solution to the high performance/high resolution flat-panel conundrum via the pursuit of 'active-addressing' each element of the viewable surface. In this mechanisation, each matrix cell

contains an additional non-linear element (normally diode, transistor or Poole-Frenkel structure) in series with the LC cell, which increases the composite multiplexing level consistent the needs this display category.

Due to the substantial nature of the market for such a highly capable display flat panel display, the detailed engineering solutions to such 'active-matrix' mechanisations are manifold and the subject to much debate as to their 'correctness'. Fortunately, these nuances are not germane to our panel topic, thus enabling us to more forward to more relevant issues on the understanding that a plurality of viable technical solutions to the AM-LCD approach have been reduced to practice and validated.

Suffice to say the active-matrix method (by whatever approach) allows a multiplex ratio of 1000:1 without difficulty thus permitting large area (~300 cm^2) display surfaces of resolution and refresh equivalent on better than achievable in the shadowmask CRT domain.

Given that such a display solution is technically and economically realizable, we must now understand how it may be employed to best effect, become mindful of its existing established deficiencies,and exploit any unique positive attributes it may possess.

In order to do this, consideration of the generic structure of the light valve itself (Figure 1) and the supportive elements of the complete multi-function display (Figure 2) may be useful. Here the light valve employs a conventional structure, placing the addressing matrix on the rear surface of the cell, the absorptive colour filter elements on the opposing front surface, in conjunction with a twisted-nematic cell structure (utilising crossed or parallel polariser/analyser elements) and a bulk scattering diffuser. Each of these attributes bounds defines or the optical performance of the cell (in regard to transmission efficiency, contrast, chromatic stability and other associated photometric parameters). Beyond the cell itself, the immediate peripheral electronics must concern itself with addressing the active array (in terms of level shifting, grey-shade coding, refresh rate) in accordance with the display image memory, thus introducing constraints in total performance with regard to image fidelity and moving artifacts.

Complementary to the electro-optic assembly is the lighting module, required to provide a high conversion efficiency, variable luminous flux source, spectrally compatible with the colour filter parameters. This element therefore, becomes the dominant influence in terms of visual dynamic range and thermal management.

Finally, the core MFD electronics provisions for the creation/acquisition of the displayed image performing such functions as:- artifact suppression, scaling, translation and overlay/windowing.

2.0 Implementation

Current solutions to the above technical challenges have now reached the level of maturity to permit a variety of viable demonstrations of capability. Flight validation of such equipment has been accomplished in diverse air-vehicles such as P-3C (part of the update IV configuration), AH-64 (in support of LH (RAH-66) risk reduction) and YF-22 (as an element of ATF source selection). However, the most vigorous investigation of the AM-LCD MFD in the flight regime, is, in all probability, evidenced in the continuing evaluation being conducted as part of a larger RAMTIP (Reliability And Maintainability Technology Insertion Program) C-130 initiative.

This C-130 architecture, as developed by Litton Canada, is configured about 6 identical AM-LCD MFDs serviced by dual 6-channel data acquisition/display processors over 125 MHz fibre-optic communications links. The system provides multi-mode operation at each display station inclusive of primary flight, navigation, engine instrumentation, advisory/caution/ warning and weather/ground map thereby offering a complete emulation of current EFIS capabilities, with mechanical, electrical and optical characteristics corresponding to the data as shown in Table 1. Via the usage of the AM-LCD technique this functional

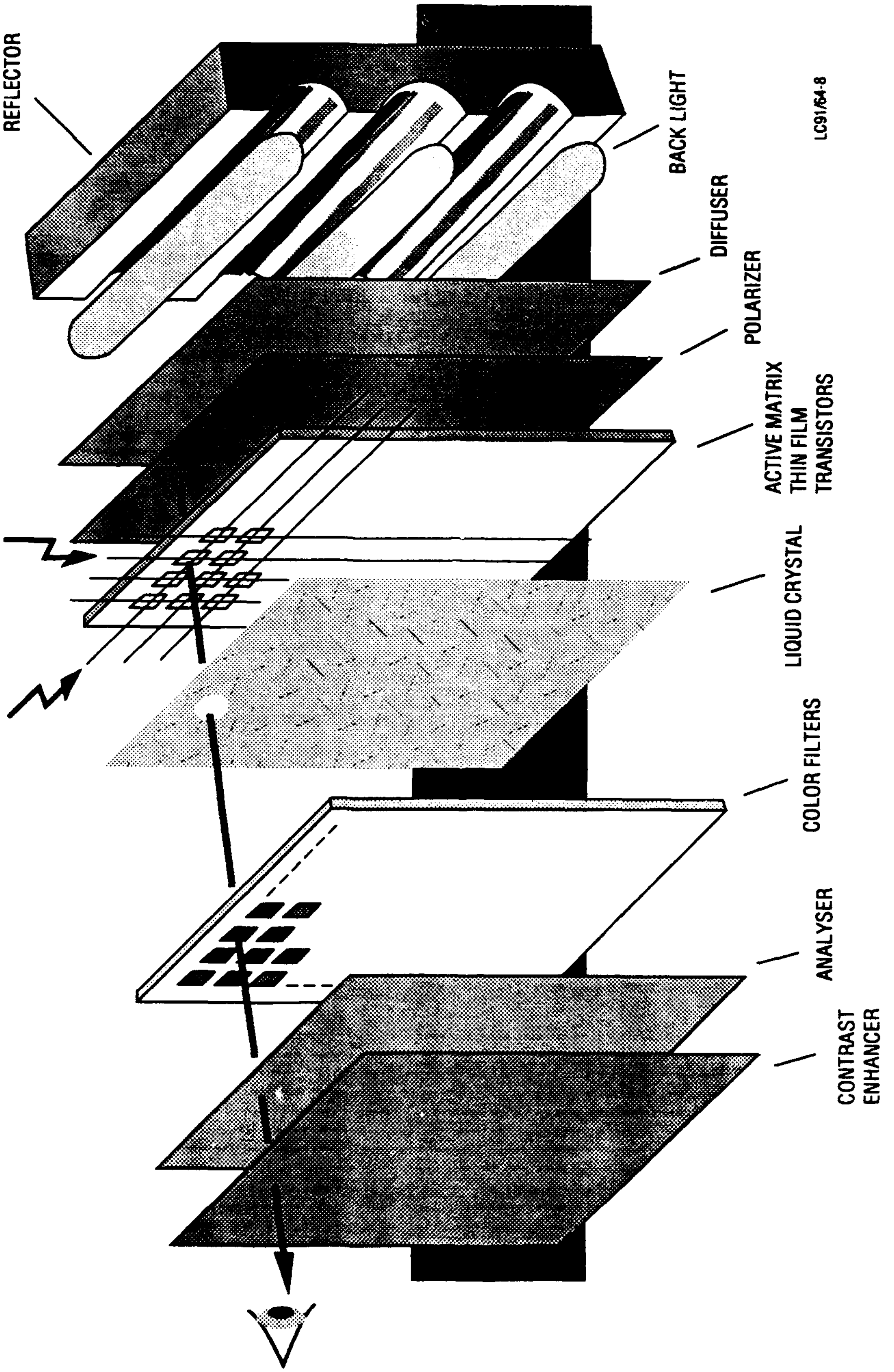

Figure 1 Active Matrix Liquid Crystal Full Color Display

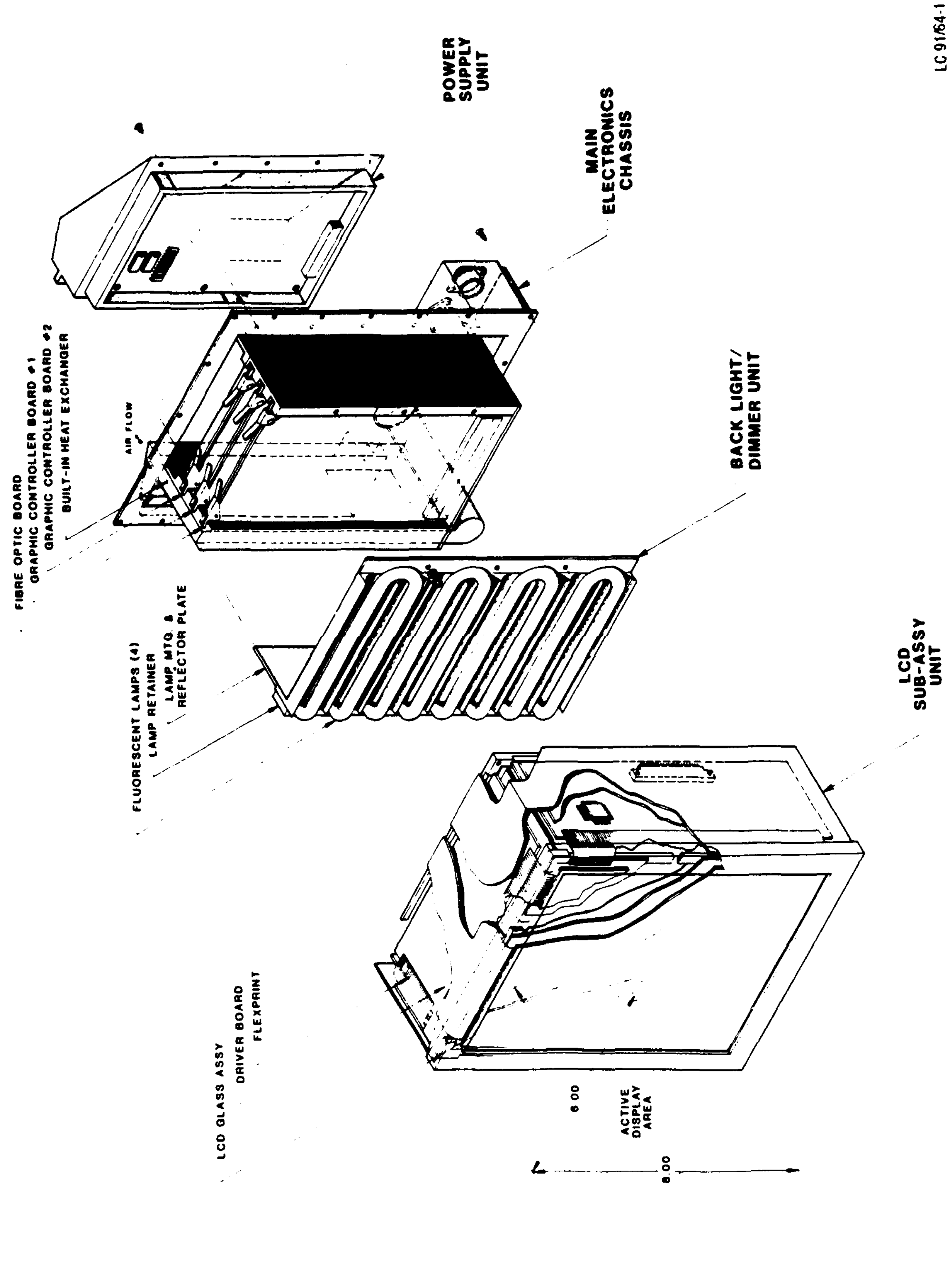

Figure 2 Practical LCD Display Unit Concept

equivalence to state-of-the-art CRT systems is augmented by the following invaluable features:

- The volume/weight economies (The LCD MFD is 6 kg and 15 cm deep, approximately 35% of its CRT counterpart) yield logistical simplicity, dry-weight reduction and retrofit savings (in the C-130 case the display suite was incorporated without significant structural alteration to the air-vehicle).

- The optical characteristics of the LCD closely parallel that of the full-colour CRT under most general lighting conditions but also provide significantly improved contrast and colour stability in the high-ambient sunlight environment, a condition more prevalent in the theater transport "greenhouse" crew-station.

- The nature of the LCD device allows the MFD to achieve an M.T.B.F. in excess of 5000 hrs, some 3-4 times greater than equivalent CRT systems. Moreover, the LCD structure is, in essence, a massively parallel light valve, thereby ensuring graceful (fail operational) degradation under most circumstances.

- The LCD MFD contains no elements requiring calibration/harmonization nor includes obscure or high-voltage electrical services. This permits the establishment of a true 2-level maintenance philosophy, which can, as required, be further condensed to an all-on-aircraft repair strategy for austere deployments.

The C-130 installation, as illustrated in Figures 3 and 4 therefore has validated the merits of LCD EFIS methods in a Theater Transport environment in the following areas:

- Significant weight reduction (~40 kg/set)

- Enhanced visual information available to crew

- Optimized air-vehicle availability/ supportability

- Competitive acquisition cost (as compared to CRT) and reduced LCC

- Minimized crew-station disturbance for retrofit/MLU usage.

While the above benefits may be impressive in themselves, they represent only a marker on a rapidly developing technology front. The C-130 system as described, passed through its formative engineering phase in 1988 and in the ensuing period considerable further advance has been realized.

3.0 Growth

At time of publication the MFDs utilized in the C-130 evaluation have yielded some 15,000 hrs of operational data, inclusive of more than 250 hrs of aircraft flight test.

Passing over the essential success of this project, many valuable lessons can be extracted from this data base to the benefit of future generations of this technology. The most significant of these rests in the area concerning the interplay between photometric performance and thermal management. The crew-station under consideration was designed in accordance with accepted Human Factors guidelines concerning the efficient assimilation of colour encoded alpha-numeric and graphical data when viewed under the broad range of airborne ambient lighting conditions. Compounded in this was the necessity to support cross-cockpit viewing of such data without incurring loss of contrast or chromatic integrity that may impede safe flight operations. Utilising the accepted TN structure in conjunction with a clear aperture (active-matrix) ratio of 55-58% this places great emphasis upon the peak output of the backlighting element thus requiring a power budget for this module in the order of 1.5W/sq.in. of viewing surface. Although not excessive as compared to an equivalent CRT systems within the reduced volume of LCD configuration, this dissipation requires the provision of forced cooling to support achievement of the desired reliability goals. Improvement on this front, toward either obtaining a

DISPLAY UNIT

OPTICAL PERFORMANCE

DISPLAY — AM-LCD 640x480 Colour, Quad Pixel Configuration
LUMINANCE — 140 FL White Field
CONTRAST — 25:1 Nominal, 3:1 at viewing angle extremes
VIEWING ANGLE — Horizontal: +/- 60 degrees, Vertical : +30, -5 degrees

COLOUR — 256 from a pallet of 2048
GREY SHADES — 16 Levels
UPDATE RATE — 30 Hz, Interlaced
REFRESH RATE — 60 Hz, Non-Interlaced

INTERFACES

FIBRE-OPTIC — Dual Redundant, 125 MHz Links
VIDEO — NTSC Standard Video Output
SERIAL — Dual Redundant RS-422 High Speed Channels

ENVIRONMENTAL

Designed to meet requirements of MIL-E-5400 Class 1AX.

RELIABILITY

MTBF - 8744 Hours min. per MIL-STD-217E parts count method.

MAINTAINABILITY

No scheduled Maintenance Requirements
MTTR - 20 minutes (MIL-STD-470)

DIMENSIONS

6.75" W, 8.75" H, 6.0" D.

POWER

28 VDC @ 125 W. (per MIL-STD-704)

WEIGHT

14 Pounds

DISPLAY PROCESSOR

HARDWARE DESCRIPTION

ARINC 429 INTERFACE
Input Ports: 2 @ 12.5 KHz
: 4 @ 100 KHz
Output Ports: 2 @ 100 KHz

1553B INTERFACE
2 Dual Redundant ports capable of either Bus Controller, Bus Monitor or Remote Terminal Mode

FIBRE-OPTIC INTERFACE
6, 125 MHz Outputs, 1.3 uM wavelength

DISCRETE INTERFACE
Input Discretes: 48 (28 VDC or Ground ref.)
Output Discretes: 16 @ 40 mA sink capability

ANALOG INTERFACE
Input : 16 @ 0-5 VDC
Output: 4 @ 26 VAC, 400 Hz

SYNCRO INTERFACE
Input : 16 - 3 wire Syncro Inputs, @26VAC, 400 Hz

RADAR INTERFACE
Video I.A.W. EIA RS-343A

SERIAL INTERFACE
8 - EIA RS-422 Hi-speed serial ports

GRAPHICS PROCESSORS
6 Independent 34020 Based GPU's
VME Bus Structure

ENVIRONMENTAL

Designed to meet requirements of MIL-E-5400 Class 1AX.

RELIABILITY

MTBF - 5082 Hours min. per MIL-STD-217E parts count method.

MAINTAINABILITY

No scheduled Maintenance Requirements
MTTR - 30 minutes (MIL-STD-470)

DIMENSIONS

20.25" L, 10.5" W, 8.5" H, (excluding mounting tray)

POWER

28 VDC @ 190 W (per MIL-STD-704)

WEIGHT

48 pounds

Table 1 C-130 RAMTIP EFIS System Technical Specification

Figure 3

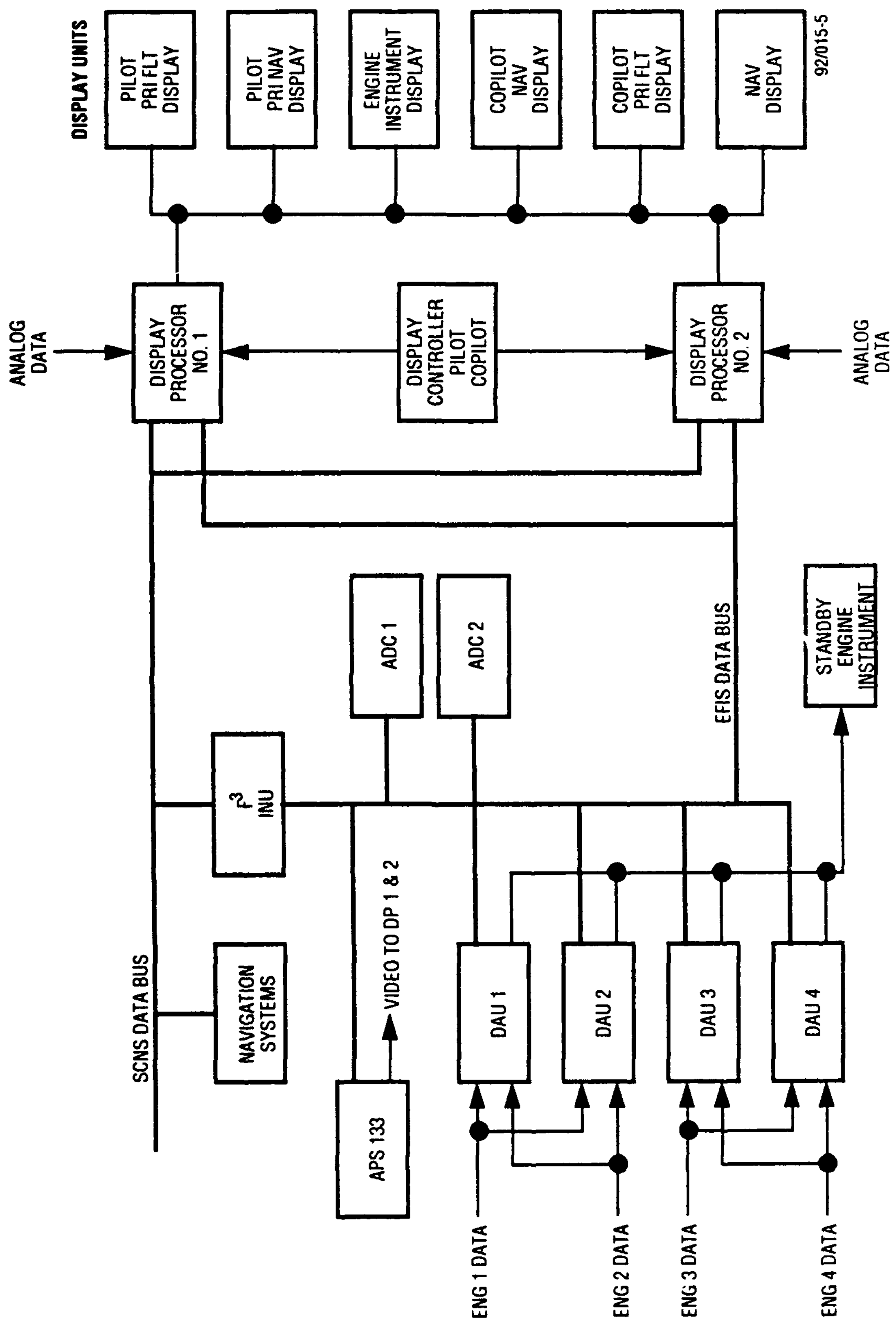

Figure 4 C-130 System Interfaces

passively cooled package or higher display luminance (at the same power level) thus enhancing grey-shade depth/minimizing chromatic desaturation at the higher ambient illumination levels would seem meritted and practical.

Opportunities for advancement in this regard can be considered on four fronts:-

Backlight/Defuser.

The existing hot-cathode fluorescent devices are probably difficult to significantly improve upon as efficient large area sources for this application. However, substantial growth in composite performance is now realizable by the more effective collection and distribution of the tube emissions. Early devices utilised parabolic on planar reflectors in conjunction with bulk dispersive diffusers. Recent developments in terms of linear involute collectors and volume hologram forward scatterers correctly applied offer some 25-30% improvement in efficiency for this element of the MFD.

Matrix Clear Aperture.

Utilising 6-8μm design rules which appear to be an economic limit for the construction of large area active-matrix arrays creates considerable loss of functio.ˋal pixel area due to the necessary tolerancing between source/gate bus structures and the associated LC pixel electrode. Any reduction in such tolerances in a conventional design has the potential to increase undesirable coupling between buses and pixel structures (create unacceptable artifacts) or in the worst case produce hard pixel defects rendering the device unusable. Via advances in process methodology and photolithographic techniques, it is now practical to 'self-align' the actual pixel utilizing the source/gate bus structures to form part of the exposure mask. These processes when applied to a matrix having cell dimensions in the order of 0.15 × 0.15 mm can increase the aperture from the previous 55/58% to approximately 70%, equivalent to an improvement in total matrix transmission by 20 - 28%.

Cell Structure/Optical Enhancement.

Existing TN structures have served well in the development of this class of display. However the requirement to include dual linear polarisers places an upper limit upon the cell transmission and the birefringent nature of the structure invokes observable chromatic variation within the viewing cone of display device. Opportunities for improvement in these characteristics are now available both by further TN cell refinement and via substitution with alternate cell constructs.

Within the mainstream TN domain, the perfection of superfluorinated eutectics and high efficiency polarising materials now permits the fabrication of cells of near minimum parasitic loss. However, associated approaches for the recovery and re-use of the rejected polarisation state have to date not proved practical within the confines of the MFD, although this work is ongoing. In terms of chromatic stability and associated off-axis contrast, two mechanisms have been shown to be practical and useful. Firstly the addition of low concentration, high-alignment dyes to the TN mixtures has been demonstrated as effective in reducing chromatic shift and broadening the iso-contrast characteristic. Secondly, the incorporation of optical retardation films whose principal axes bear specific relationship to the cell alignment direction have proven effective in stabilising wave-length dependent ellipticity of the polarisation state of the transmitted light which forms the underlying cause of oblique angle chromatic shift.

Beyond the TN method, previously known but less developed techniques that do not require the incident light to be of a linearly polarised state are now approaching useful maturity. Detailed comment on these materials is beyond the scope of this paper however, progress in both the Heilmeier (single polariser) and Suspended Particle areas is relevant in this regard.

Colour Generation.

As shown in Figure 1, the conventional method for obtaining full colour performance from this class of

display is to employ a front surface, mosaic colour filter registered to the matrix structure and possessing transmission spectra matched to the emission bands of the back-light. Although functional this approach carries with it some significant penalties, in terms of total light loss (due to absorptive nature of filters) and in the tendency to utilize broad transmission spectra (in order to minimize light loss) which results in a relatively de-saturated colour gamut. A number of approaches have been advanced and evaluated with the intent of circumventing the absorptive loss mechanism. Of these, the frame-sequential method is best known, however this does not easily adapt itself to the high performance MFD due to the requirement to maintain high frame rates (~200Hz) which are inconsistent with the current switching characteristics of the LC cell. A more promising solution utlises a luminescent mosaic in place of the absorptive structure in an inverted fashion, whereby each element is excited to emit in its chosen spectra via a back illuminant attuned to the appropriate absorption band. By either mechanism it can be shown that overall conversion efficiency (lumens/watt) may be improved by a factor of 2 as compared to an equivalent multi-colour absorptive system.

4.0 The Future.

At the present time the AM-LCD approach has shown itself capable of executing an effective visual emulation of the accepted CRT primary flight instrument. The C-130 deployment referenced herein provides one of the more substantial demonstrations of this capacity, however several analogous developments have also been reliably reported. In the various Centres of Expertise technical improvements, (as referenced in Section 3), continue to be incorporated which in the immediate future will render the AM-LCD/CRT visual equivalence debate passe. Moreover, upon achieving this plateau, the unique positive attributes of this technique will become more obvious and open to useful exploitation.

At the display surface level the following topics present themselves as relevant:-

Resolution/Modulation.

For the flight regime current AM-LCD instruments have shown themselves capable of working reliably at resolutions in the order of 0.15mm/cell in conjunction with 20-30 discernible grey-levels. Advancement on these fronts is keyed primarily to process engineering maturity/characterization and not to any immediate technical barrier. It is therefore reasonable to expect the resolution to more toward 0.08-0.10mm/cell with grey-level capacity of 150-200 without difficulty or delay. These performance parameters will transcend our prior knowledge base in terms of avionics CRT characteristics and therefore cause us to revisit some of our established cognitive and perceptual ground rules. On a more practical front such resolution/modulation flexibility will afford the construction of display devices which exactly echo the formats of advanced electro-optic sensor arrays, thus mitigating informational loss and artifact generation.

Area/Form-Factor.

As a producible/deployable device the AM-LCD industry is currently constrained to devices in the 400cm2 range containing 1-1.5M addressable elements. Extension of these boundaries will be contingent upon:-

- Development and maturity of cost-effective process equipments suitable large area substrates.
- Technological advancement at semi-conductor device level to satisfy the more stringent parametric requirements of the larger area/denser arrays.

These issues are non-trivial however both industry momentum and existing scientific knowledge at the device level, suggest that the 1200 cm^2 device containing 3-4 M elements should become a usable commodity at the avionics level within the next 2-3 years.

Additionally this growth should have two effects at the MMI level:-

Firstly we will start to realise in flyable configuration the more visually integrated crew-station that has received substantial laboratory consideration to date. Secondly, the push forward in area/density will also create the capability and knowledge to more economically and flexibly engineer/produce devices of more modest proportions. That is, the crew-station designer and human-factors engineer with the afforded to opportunity to tailor the viewing surfaces of each requirement in an optimal fashion without prohibitive cost.

Secondly, at the architectural level the volume efficiencies (here today) and power economies (coming) of the AM-LCD provide great flexibility in incorporating truly distributed flight information systems in future air-vehicles. Discussion of the merits of such techniques in terms of LCC, fault tolerance, damage containment and logistics as compared to centralised systems are beyond this paper's scope however, it should be noted that AM-LCD is the enabling technology for consideration of these architectures without functional compromise.

Finally while we continue, in the main, to employ the AM-LCD to emulate emmisive devices such as the CRT, its intrinsic properties as a discretely addressable spatial light modulator should not be overlooked. At the crew-station level we continue to evaluate the value of stereopsis as a flight aid. Whilst research evidence shows promise the practical realization of such a display mode for general cockpit usage continues to be problematic. As has been demonstrated, the properties of AM-LCD (Resolution, video compatibility, discrete addressability) when used in conjunction with appropriate lighting constructs can provide an autostereoscopic capability that may prove suitable for such deployment.

5. Conclusion

Substantial global financial and technical investment has produced an AM-LCD body of knowledge suitable for avionics usage. A small number of centres of expertise have successfully transitioned this technology into the airborne environment and established its practical value at the development level. As a result we will witness operational deployment of such devices in a number of air vehicles in immediate future. These initial applications will provide parity of MMI performance with existing systems while offering the user logistical on economic benefit. However, ongoing AM-LCD development is and will continue to enable new classes and kinds of display devices that will have profound and valuable impact upon our man-machine interface concepts.

LES ECRANS A CRISTAUX LIQUIDES
REMPLACANT DU CRT ET CLE DES FUTURS COCKPITS

par

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Sommaire :

Due to well-knowed advantages such as a small weight, reduce volume , low consumption, lisibility (under high brightness) reliability, to mention the most important, the flat panels have already started to replace the CRT in the world of military aircraft.

Among flat panels, the liquid crystal active matrix display is the most advanced. Full colors and grey shades displays are mass produced for commercial applications, and new military cockpits, both for airplanes or helicopters are based on that technology (Rafale is used as example to illustrate the advantages of LCD compare to CRT).

Furthermore liquid crystal panel is a technical key which will help future cockpit concepts to wake-up to life. The head level display and the large interactive display are among them. Projection technics and liquid crystal cells are merged to take benefits of liquid crystal, removing the drawbacks (that notion is illustrated by a brief description of an head level display demonstrator).

Abréviations

LCD	:	Liquid Crystal Display
AMLCD	:	Active Matrix Liquid Crystal Display
THT	:	Très Haute Tension
DEMVAL	:	Démonstration Validation
VTL	:	Visu Tête Latérale
TRC	:	Tubes à Rayons Cathodiques
HLD	:	Head Level Display

1. GÉNÉRALITÉS

Les propriétés des cristaux liquides sont connues et utilisées de longue date et leurs applications sont apparues dans le domaine de la visualisation avionique depuis quelques années.

Parmi les autres technologies d'écrans plats, (plasma, electroluminescent, diodes ou tubes à rayons cathodiques plats) seules les matrices actives à cristaux liquides concurrencent les écrans à tubes classiques dans le domaine avionique.

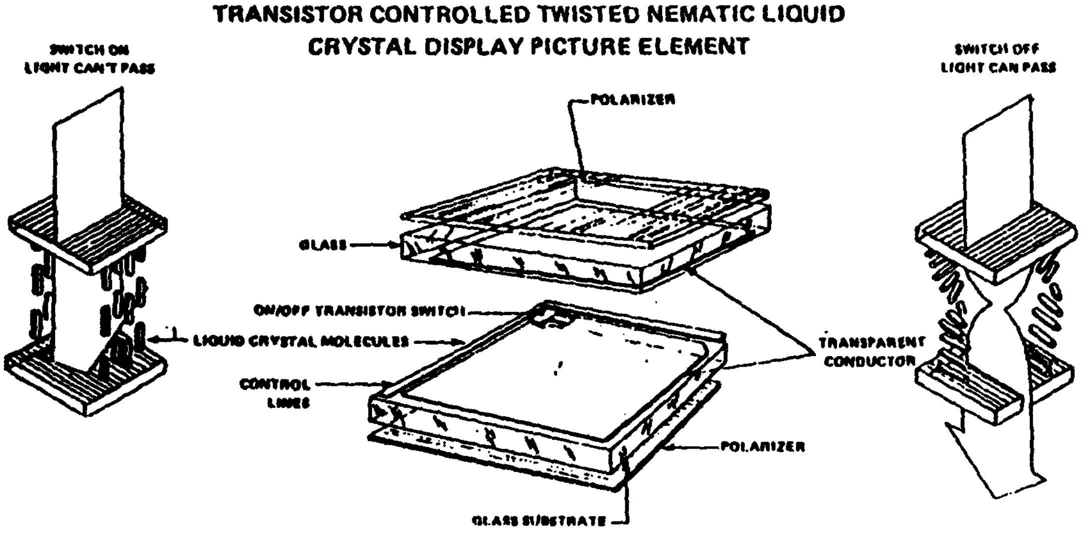
La couleur est le problème le plus complexe rencontré par les autres tehnologies(plasma, electroluminescent) bien que quelques réalisations en laboratoire laissent paraître quelques possibilités.

Cependant c'est l'aptitude à l'industrialisation qui fait que les cristaux liquides sont aujourd'hui en production de masse (écran pour PC portable, notebook, cartographie pour voiture) et totalement crédible pour les applications de type avionique militaire.

D'où les nombreux appels d'offres requérant des cockpits munis d'écrans à cristaux liquides (F22 américain, C130 ou C141, Rafale, Hélicoptère Tigre ou LH) surtout après la réussite des essais en vol de la version DEMVAL de l'ATF, et du Rafale.
Dans la majorité des cas, les écrans spécifiés sont de type matrice active (AMLCD), association d'une matrice de transistors ou de diodes en silicium et du cristal liquide dit nématique en hélice.
Ces écrans à cristaux liquides à matrice active n'émettent pas de lumière mais la transmettent, dissociant ainsi commande et puissance lumineuse, permettant résolution, piqué d'image, niveaux de gris, sans prejuger du niveau de luminosité.

2. LES VISUALISATIONS TÊTES BASSES LCD

La grande majorité des nouveaux cockpits



* 2 polariseurs linéaires placés l'un devant l'autre transmettent ou absorbent la lumière.
* le cristal liquide placé entre les polariseurs a au repos une structure en hélice qui modifie la polarisation de la lumière (90°). Sous l'action d'une tension, cette structure est détruite, la polarisation de la lumière n'est pas modifiée.
* le sandwich (polariseurs et cristal liquide) a alors la propriété de transmettre ou d'absorber la lumière suivant la tension appliquée.

Figure 1 : Principes des écrans LCD

d'avions ou d'hélicoptères (rétrofit ou appareils neufs) demandent des écrans à cristaux liquides. Les plus remarquables réalisations dans le domaine militaire sont l'YF22 US (LOOCKHEED phase DEMVAL - Technologie General Electric initiale - écrans 6.25"x4" et 6.25"x6.25"), et l'avion Rafale (Dassault - Technologie Thomson-LCD évolution de celle de
General Electric - écrans 5"x5").Ainsi que l'hélicoptère Tigre.

Nous allons décrire cette dernière pour illustrer notre propos.

Dans le cadre du programme de "Visualisation Tête Laterale (VTL) du Rafale D", les spécifications dimensionnelles de l'équipement, dues à la forme profilée de la cabine, ont imposé la technologie LCD (voir figure 2.1).

Fonction :

La visualisation tête latérale est une visualisation intégrée multimode couleur à cristaux liquides connectée directement au bus numérique avion (1553B). Elle intégre dans le même volume les fonctions d'interface, de calcul et de visualisation (fonctions réalisées habituellement en 2 équipements : la visu et son boitier de calcul).

Architecture Electronique :

Autour d'un écran LCD 5"x5", la VTL regroupe (voir figure 2.2) :
- une visualisation LCD et son éclairage,
- une électronique de génération d'images regroupant :
. la fonction traitement et son interface avec le bus numérique avion,
. la fonction génération d'images incluant le processeur graphique, une électronique de lissage de tracé associée et une interface de traitement vidéo STANAG 3350.
. une fonction interface de restitution de mission
- l'alimentation basse tension de l'équipement
- une interface de dialogue constituée d'un écran tactile et de son contrôleur associé.

Performances
--> L'Optique
. Ecran LCD 5"x5" haute résolution équipé de son système d'éclairage arrière.

Cet écran intégre un système de préchauffage permettant une mise en oeuvre accélérée de l'équipement lors de démarrages aux basses températures.

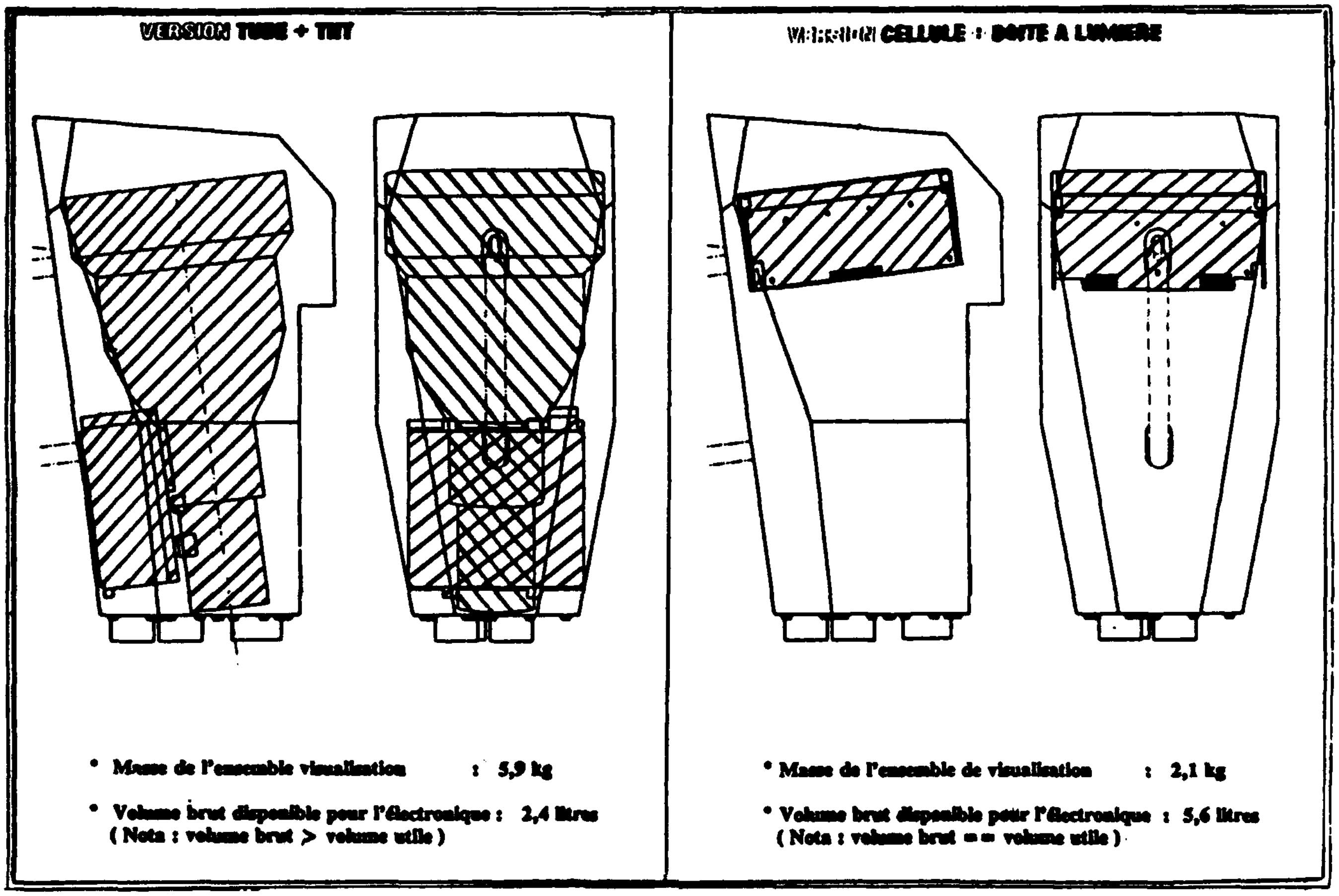


Figure 2.1 : Encombrement comparé Tube LCD

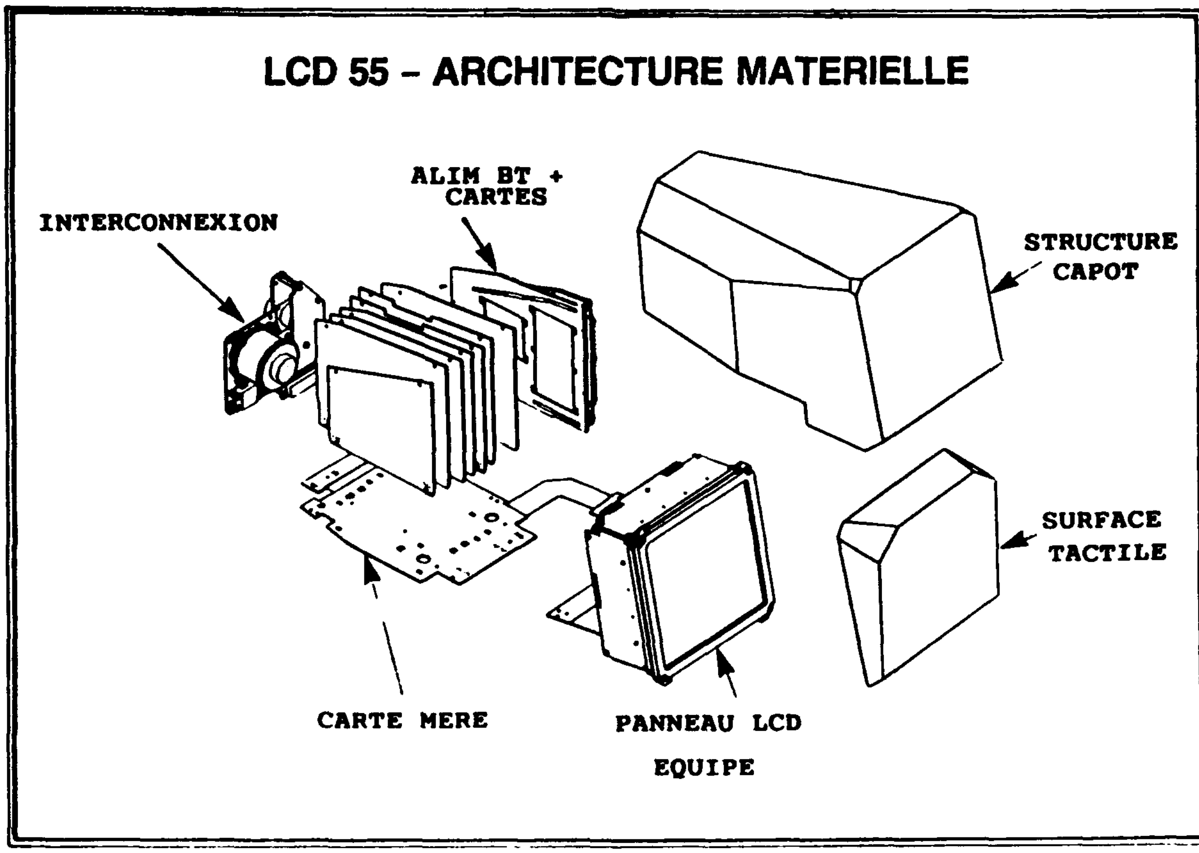


Figure 2.2 : Architecture Interne de la VTL à Cristaux Liquides

. Résolution de 416 x 416 pixels couleurs au pas de 310 microns

Un pixel couleur est constitué d'un quadruplet R,V,V,B au pas de 155 microns.

. Technologie militaire à matrice active (TFT en silicium amorphe) et Crystal Liquide nématique en hélice.

. Lampes à cathodes chaudes permettant un haut rendement lumineux (>60lumen/watt).

. Luminance du blanc > 470 cd/m2 en sortie de produit.

. Contraste sous fort éclairement > 5 : 1 (100000lux à 45°).

. Compatibilité JVN
--> L'électronique :

. Génération graphique :

Développement de circuits VLSI spécifiques : Processeur graphique et processeur de lissage spécialisés à la technologie LCD (techno 1 micron, 35000 portes).

. Circuits "DRIVERS" spécifiques à la commande de l'écran LCD.

--> L'écran tactile :

Cet écran remplace le traditionel poste de commande à touches mécaniques.

--> Mécanique :

. Dimension hors tout : (LxPxH) 367x168x210
. Volume 9 litres
. Poids 7 kilogrammes

3. PERFORMANCES DES CRISTAUX LIQUIDES EN VISION DIRECTE

Nous allons dans ce paragraphe détailler les performances les plus remarquables de cette technologie, celles qui justifient l'engouement actuel. Nous nous sommes basés pour ce faire sur l'expérience de Sextant Avionique dans ce domaine et notamment sur les travaux effectués dans le cadre des programmes Rafale et Tigre.

Encombrement/poids :

Les écrans à cristaux liquides font partie de la famille des écrans plats et permettent une réduction considérable du volume et du poids en comparaison avec les tubes à rayons cathodiques.

La profondeur due à l'écran est de l'ordre de quelques centimètres auquel il faut ajouter la source lumineuse, suivant les performances requises. Un moniteur peut n'avoir que 10 à 20 centimètres de profondeur à comparer avec les trente à quarante centimètres d'une visualisation à tube (avionique complet avec alimentation, protections, connecteurs,...).

Lisibilité sous fort éclairement :

C'est ici un des points majeurs de cette technologie et qui mérite de s'attarder. Comme il a été indiqué dans le paragraphe précédent, les écrans à cristaux liquides ne sont pas émissifs mais transmissifs ; aussi les 2 critères essentiels permettant de mesurer leur qualité sous fort éclairement sont :

- la transmission,
- la réflectivité spéculaire et la réflectivité diffuse.

La transmission varie suivant les fournisseurs et la technologie de 3 à 5 % pour un écran couleur. Ce qui permet, suivant l'éclairage arrière d'obtenir une luminosité dépassant les 700 cd/m2.

La réflectivité (spéculaire ou diffuse) des écrans LCD peut être extrêmement faible de l'ordre de 0.8% en spéculaire (voire inférieure à 0.5%) et de 0.15 % en diffus (jusqu'à 0.1%) pour peu que les matériaux constituants l'écran aient été choisis en tenant compte de ce critère.

Cette caractéristique essentielle se traduit par la possibilité de lire facilement les informations affichées (vidéo alphanumérique et graphique) quelque soit les conditions de luminosité extérieure. Des contrastes ratios supérieur à 5 ont été obtenus avec cette technologie; mesures effectuées dans les conditions de la norme MIl-L-85762A (10000 fc, 2000 fl).

Disponibilité/Fiabilité :

Nous n'avons pas encore assez de recul dans le domaine des matrices actives pour être catégorique sur ce point. Cependant
nous allons développer 3 idées qui nous font penser que là encore cette technologie est intéressante.

Les cristaux liquides non actifs (dédiés ou multiplexés) utilisés depuis plus de quinze ans ont montré une fiabilité extrêmement élevée.

Les écrans à matrice active sont constitués de millions de transistors ou diodes. La perte d'un de ces élements ne remet pas en cause la qualité de l'information transmise. Nous dirons que ces écrans sont tolérants aux pannes.

Les alimentations nécessaires au fonctionnement de la visualisation sont de type basse ou moyenne tensions (y compris la boite à lumière) et non pas THT comme les CRT.

Qualité d'image/Précision :

Les AMLCD offrent ce double avantage de la numérisation (matrice) et de l'effet optique analogique. La transmission de l'information du capteur jusqu'au pilote peut être entièrement numérique préservant son intégrité et sa qualité, plus de jitter ni de bruit.

Electronique :

Les LCD nécessitent de nouvelles fonctions électroniques :
boite à lumière,
gestion écran LCD,
évolution des fonctions tels le traitement vidéo et graphique.

Mais, avec la suppression de la THT, le bilan en terme de compléxité, encombrement et consommation est largement positif.

Futur développement :

Ce tour d'horizon des performances des AMLCD ne serait pas complet si nous n'évoquions pas quelques domaines ou des améliorations sont à trouver. En premier lieu l'angle de vue important demandé par les avions de transports ou certains hélicoptères; de gros efforts techniques et financiers sont effectués qui doivent permettre de trouver le composant optique qui augmentera le contraste.

Les écrans LCD deviennent plus grands (jusqu'à 14" de diagonale), les caractéristiques générales sont relativement constantes (résolution, transmission, architecture électronique).
Si, dans le domaine de l'angle de vue, un effort doit être fait pour permettre une vision pilote/copilote, en contrepoint le concepteur de cockpits se doit de prendre en compte cette caractéristique des écrans LCD dès la création de la planche de bord.

4. LES VISUALISATIONS EN PROJECTION :

La technologie LCD ne semble pas pour l'instant compatible de très grand format mais de très haute définition. Dans la course pour le marché de la télévision haute définition, de gros investissements sont faits pour le développement de valve à cristaux liquides de résolution descendant jusqu'à 40 microns de pas et moins, permettant la fabrication de TVHD.

Une évolution similaire nous semble pouvoir se faire dans la visualisation avionique, non seulement pour réaliser des moniteurs haute définition ayant des performances de volume de poids et de consommation meilleures que celles des TRC, mais aussi pour réaliser des visualisations collimatées (visualisation tête moyenne).

Ces visualisations collimatées offrent 2 avantages essentiels:

- Collimatée à l'infini, l'information affichée sur l'écran semble en continuité avec le viseur tête haute conduisant à un accès rapide des données par le pilote.

- La densité d'informations présentables sur une telle visualisation n'est pas proportionnelle à la surface de l'écran mais au champ de vue.

4.1 Visualisation tête moyenne :

Nous allons rapidement présenter ce que peut être une telle visualisation se basant sur une maquette réalisée dans le cadre d'un marché d'étude, et en détailler les performances.

Les caractéristiques générales de cette maquette sont :

- Champ d'une vingtaine de degrés
- Capacité couleur (RGB / >16 niveaux de gris)
- Résolution nombre de points >230.000

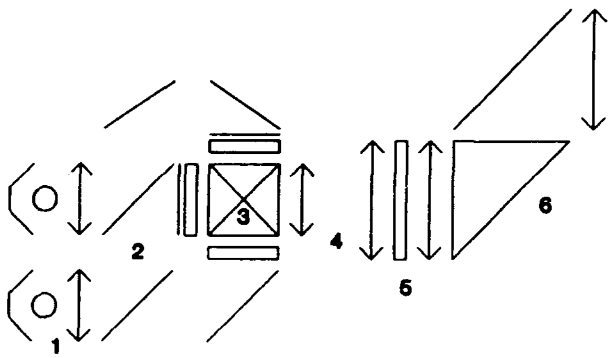
Architecture Optique :

La figure 4.1.1 montre l'architecture optique comportant des éléments holographiques.

Cette architecture utilise comme source d'image 3 LCD superposés et en projection. Complétée par une optique de collimation, elle répond aux contraintes avioniques :

- la lampe est de type halogène (simplicité, taille réduite...),

- une deuxième lampe a été rajoutée afin d'augmenter la sécurité du système,
- l'utilisation de composants holographiques a permis une réduction du volume total.
- une compensation colorimétrique est possible:
- elle permet d'éviter une dérive des couleurs dans toute la gamme d'utilisation (jour/nuit)
- l'optique de projection a un encombrement réduit (l < 140mm) et utilise des surfaces complexes (asphèriques...).



1. Lampes
2. Séparateur de couleurs
3. Mélangeur
4. Optique de projection
5. Diffuseur
6. Optique de collimation

Figure 4.1.1 Architecture optique

Architecture électronique

Elle est composée :
- d'un traitement des données vidéo pour s'adapter parfaitement aux caractéristiques optiques et électrooptiques des LCD,
- d'un système de gestion qui prend en compte l'environnement intérieur et extérieur de la visualisation et modifie en conséquence le traitement vidéo.

Performances

- Champ :
. total : 20° x 20°
. instantané : 20° x 20°
. Cet écran occupe le champ visuel équivalent à celui qu'occuperait un écran de 30 centimètres de côté (12"x12") placé à 80 centimètres de l'oeil du pilote.

- Luminance :
. R (605-640 nm) > 150 cd/m2
. V (500-590 nm) > 400 cd/m2
. B (440-460 nm) > 80 cd/m2
. blanc > 600 cd/m2

- Contraste (sous un éclairement de 100000lux à 45° d'inclinaison) :
. R > 4:1
. V > 10:1
. B > 3:1

- Colorimétrie :
. La figure suivante montre le diagramme de couleur.

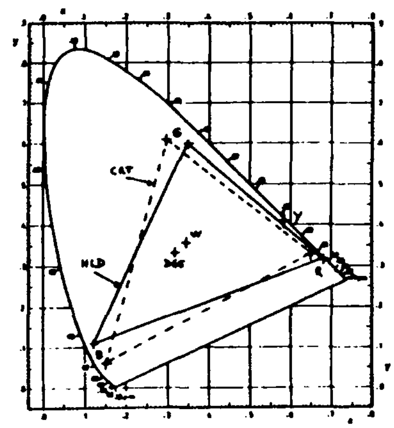


Figure 4.1.2 : Diagramme des couleurs

4.2 Visualisation de type rétro projecteur :

Ces visualisations se présentent comme des moniteurs en vision directe mais le principe de génération d'image est celui d'un projecteur.

L'intérêt majeur de ce type de visualisation se situe dans le domaine des grands écrans de forte résolution (Cartographie, Radar...), d'un point de vue technique les écrans LCD sont des composants optiques, il faut :
utiliser leurs caractéristiques sans contraintes d'angle de vue,
dégager la génération d'images des contraintes cockpits (un seul type d'écran LCD pour différents moniteurs).

L'architecture d'ensemble est identique à celle des visualisations têtes moyennes, seule la dernière couche optique, la collimation, est supprimée. Il est de plus nécessaire d'agrandir l'image (voir figure 4.2.1).

Performances objectives :

- Définition : jusqu'à 1000x1000 points couleurs
- Luminosité : 200 cd/m2 aujourd'hui jusqu'à 400 cd/m2
- Contraste sous 100000 lux suivant la luminosité de 2:1 à 4:1.

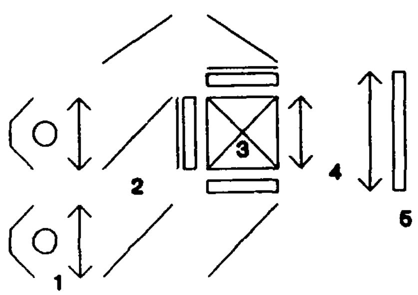
Analyse critique

La projection à base d'écrans LCD est une des

voies qui permettront de réaliser des télévisions haute définition (TVHD). De gros investissements sont consentis dans ce domaine pour la réalisation de valves au format 4/3 ou 16/9 ayant un pas de l'ordre de 40 à 60μ.

La projection permet la conception d'un coeur "génération d'images" indépendamment de l'écran qui sera présenté à l'utilisateur, d'où la possibilité de concevoir des visualisations grand format et haute résolution adaptées au besoin des utilisateurs à partir de matrice standard.

L'industrialisation de ce type de produit permettra de compenser la complexité inhérente à ce système. Cependant, ces visualisations seront plus plus complexes que les visualisations LCD en vision directe.



1. Lampes
2. Séparateur de couleurs
3. Mélangeur
4. Optique de projection
5. Diffuseur

Figure 4.2.1 Architectui : optique

5. LES COCKPITS LCD

La conception des cockpits a suivi l'évolution technologique. Les écrans à tubes à rayons cathodiques ont remplacé les visualisations electromécaniques, permettant par la suite de regrouper les informations sur des écrans de grande taille.

Les TRC sont aujourd'hui remplacés par les LCD. Nous nous proposons de faire un rapide survol des potentialités que cette nouvelle technologie offre aux concepteurs de cockpits. Les figures 5.1, 5.2 montrent l'évolution du cockpit de l'hélicoptère SUPER PUMA et la figure 5.3 est une illustration du cockpit de l'avion Rafale D à base de LCD en vision directe ou en projection.

De nouveaux concepts de visualisation apparaissent type notebook, cartographie ou bibliothèque électronique. Le faible encombrement des écrans à cristaux liquides, leur résolution et la qualité d'image, associés à une consommation réduite prennent tout leur intérêt.

A plus long terme, les besoins des utilisateurs nous semblent doubles :
- plus d'informations de meilleure qualité,
- un accès facile à ces informations (ergonomie).

La technologie LCD permettent une avancée dans ces deux domaines :
- haute résolution et niveaux de gris permettent qualité d'image et densité d'informations,
- écran numérique, les LCD s'intègrent parfaitement dans les chaines de traitement du signal en conservant la qualité d'image (zoom, translation, médaillonage, régie vidéo, ...),
- visible quelle que soit l'ambiance lumineuse, le pilote a toujours accès à l'information,
- en projection l'écran s'adapte aux besoins en terme de géométrie et d'ergonomie.

<u>Références :</u>

D. PLANTIER e.a. (1991), An Avionic Full-Color Collimated Head Level Display, SID 91 Digest.
P. MICHEL Visualisation LCD Couleur pour l'Avionique, VISU 91.

Discussion

QUESTION J. DANSAC

Pensez vous que la technologie LCD pourra être appliquée dans le futur aux HUD ou HMD?

REPLY

Cette technologie n'est pas immédiatement adaptable: il faudrait passer de dimensions de pixels de 40um à des pixels de 15 a 25 um.

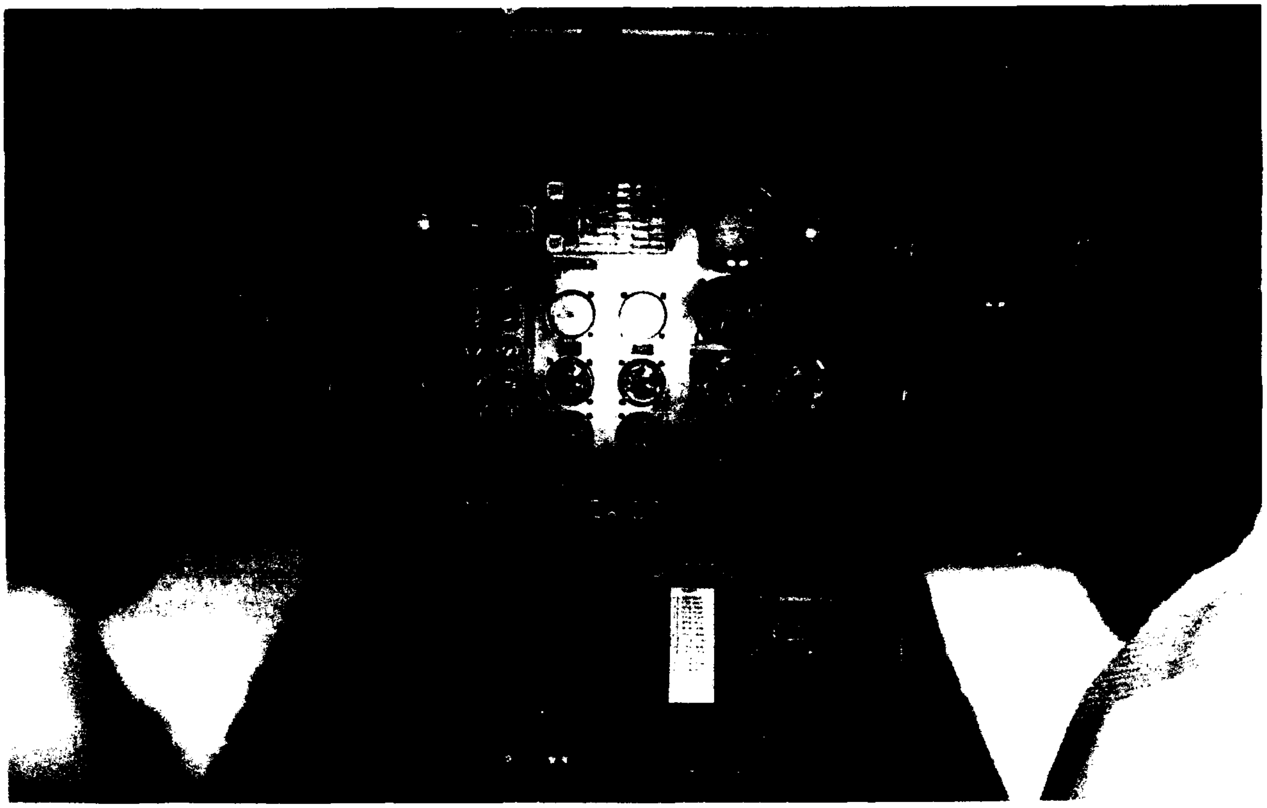


FIGURE 5.1 : COCKPIT GENERATION
(HELICOPTERE SUPER PUMA)

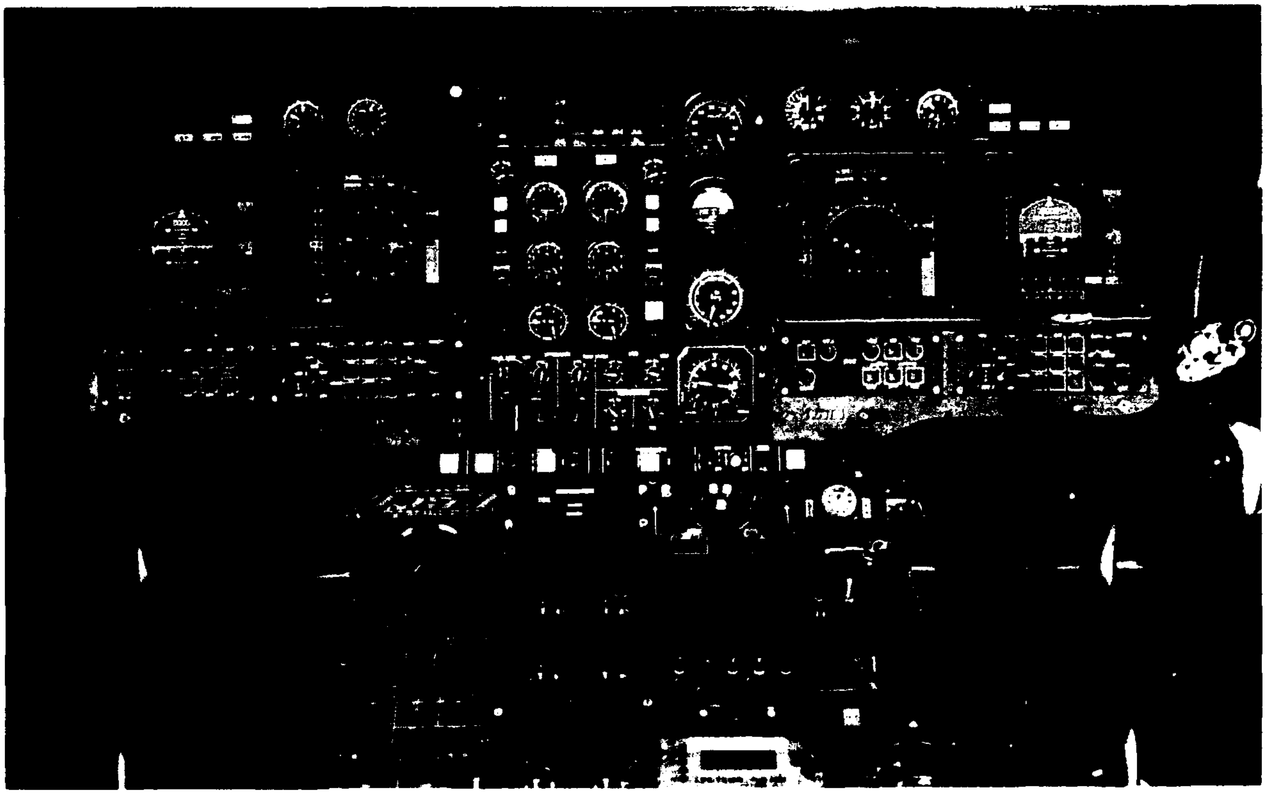


FIGURE 5.2 : COCKPIT GENERATION CRT
(HELICOPTERE SUPER PUMA)

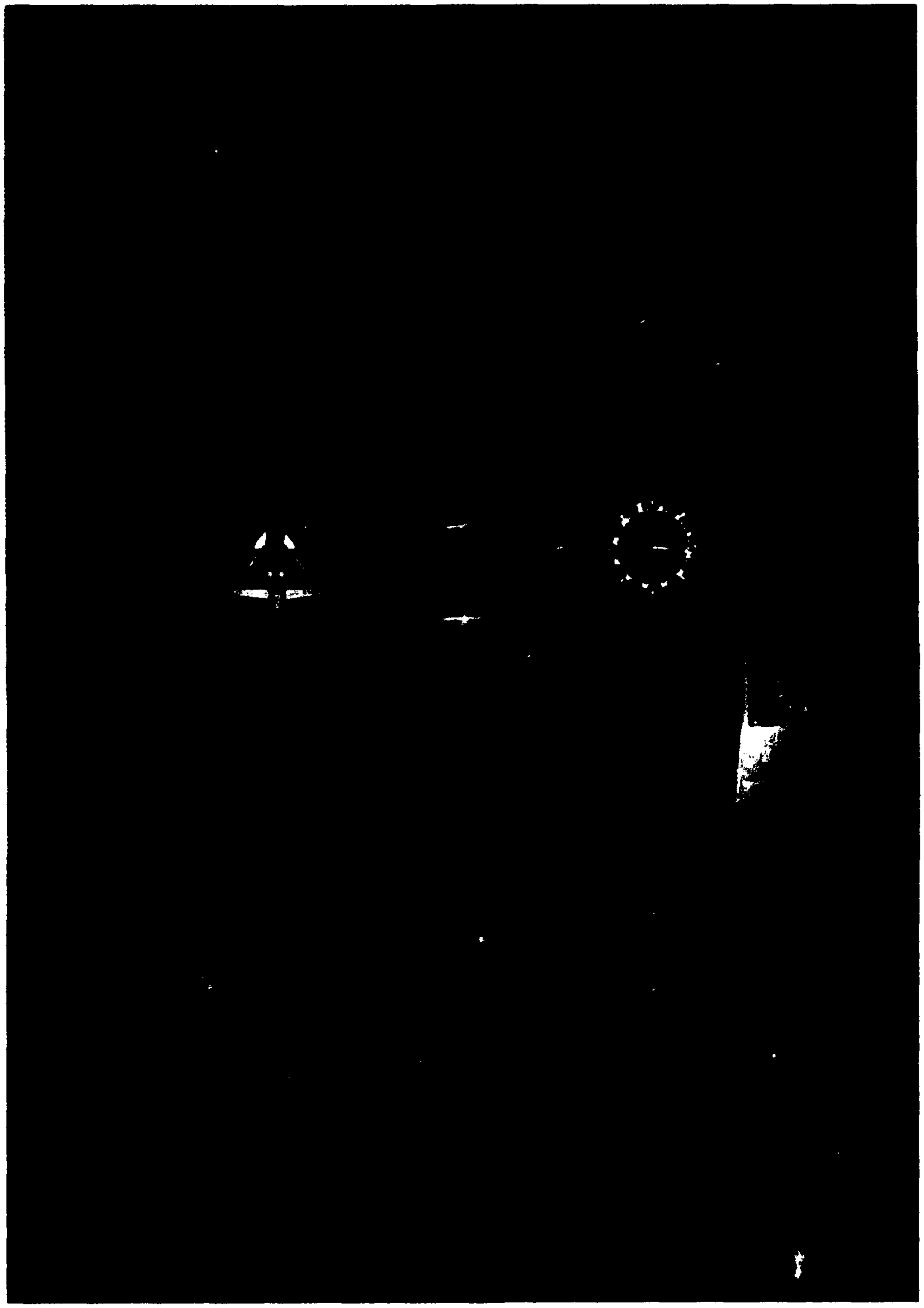


FIGURE 5.3 : COCKPIT NOUVELLE GENERATION

(RAFALE D)

ADAPTIVE AUTONOMOUS TARGET CUER

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CONTENTS

ABSTRACT

The Navy is exploring the use of an adaptive autonomous target cuer that is potentially more reliable than existing systems. Variations in the operational environment and target type are major factors that can degrade an autonomous sensor-based cuer performance. The solution presented here is to have several parallel algorithms for each functional component in our target cuer. Each algorithm is tuned to handle a particular situation. Based on certain indicator functions, a fuzzy logic expert system controller will select the most suitable algorithm and optimal parameters to process the sensor data.

Although the proposed system is essentially comprised of conventional components such as image preprocessing, feature extraction, and correlation, it distinguishes itself because of its use of fuzzy logic in decision making and its adaptive nature. In designing an expert system, we will select the optimal set of indicator functions using the Taguchi process-control methodology. Preliminary results will be presented.

INTRODUCTION

An autonomous target cuer on a land attack aircraft will enable the pilot to launch the weapons at a greater range with confidence, reduce the time of exposure of the aircraft to threats, and improve the survivability and effectiveness of the aircraft. Improved target cuer performance, namely higher target-detection rate and lower false-alarm rate, will enhance the acceptance of such a system and encourage its use by the flight crew.

However, the current generation of target cuers has not gained wide acceptance. These systems perform satisfactorily under the controlled or tested situation, but variations in operational environments adversely affect system performance and render them unreliable. Our solution is to build a cuer that has switchable modules, with each individually tuned to operate optimally under a specific condition. This is in line with the modern trend of machine intelligence which is to build highly specialized expert systems (Ref 1). The proposed cuer is essentially several narrowly focused cuers tuned to operate under prescribed conditions. A controller will select which special purpose cuer to use based on the input from on-board sensors, from the pilot or operator, and from the sensed image itself.

CONTENTS AND ORGANIZATION

In the next section, a brief review of previous work in this area and their relationship to the present study is given. Then, we will discuss a system overview of a generic adaptive autonomous cuer. Next, the structure of the fuzzy logic controller is explored with the introduction of a step-by-step recipe for selecting fuzzy inputs and rules. Lastly, we will set up a simple controller that will select an appropriate algorithm to perform edge extraction on a two-dimensional intensity image.

PREVIOUS WORK AND THE PROPOSED APPROACH

Many studies on adaptive image processing are reported in the literature (see Ref 2, 3, and 4). However, these studies focused on adapting filter parameters to varying local statistics within a given non-stationary image.

Previous work that resemble the approach taken here has not been widely publicized. Of the few relevant reports found, the adaptive nature of the system was only implied and not explicitly explained or stated. For instance, Ref 5 discusses a missile defense system that would select in real-time various image processing filters based on the nature of the input image. However, the algorithms selection methods were not discussed.

The approach described in this paper is unique in two respects. First, the controller selects the appropriate filter and parameters based on the nature of the sensed input image, such as image statistics, and the operational environment. Second, the algorithm and parameters to be used are determined by experimentation with both real and synthetic images.

A fuzzy logic expert system shell was chosen to develop the controller because of the existence of fast

fuzzy logic hardware. It is more human-like in decision making and the software is easy to use. We use the Taguchi method to select the critical input parameters to the fuzzy logic controller and to set up the fuzzy rules because it is simple to implement and is less time consuming than an exhaustive parameter study. A brief introduction to fuzzy logic and the Taguchi method is presented in Annexes A and B, respectively.

COMPONENTS OF THE ADAPTIVE AUTONOMOUS CUER

The adaptive autonomous cuer is divided into several structural components as shown in Fig 1.

The *preprocessing* step reduces noise in the image. Optionally, the volume of data can be reduced by using a region-of-interest locator and processing only this sub-image region.

The *feature extraction* module further reduces the data volume and transforms the pixel-space image to a feature-space representation. A good feature representation simplifies the model correlation or matching task. Some examples of features are edges, corners, area, volume, and reflectivity contrast. The output of this module is a feature-space map of the original image.

The features obtained from the image are then matched in a *correlator* with those generated by the target model through the simulated seeker data path (shaded area in Fig 1). The output of the module is a probability of target presence.

OVERVIEW OF FUZZY LOGIC CONTROLLER

Fig 2a and 2b shows a block diagram of a fuzzy logic controller for adaptive image processing and the incorporated fuzzy logic expert system, respectively. The evaluation box on the left (Fig 2a) calculates parameters that will indicate the type and quality of the image. Some examples are mean, variance, average gradient, and edge density. These indicator functions and information about the operational environment are input to a fuzzy logic expert system that will decide which filter and parameters to use in processing the image.

The rules in the fuzzy logic expert system are initially set up using hueristics and intuition with help from a human expert. Refinement and addition of new rules are achieved through experimentation with real and synthetic images. The procedure is outlined below.

1. Establish a uniform performance measure for the filter. For preprocessing, examples are signal-to-noise ratio or percentage of speckles removed. For edge extraction, the following formula is appropriate.

$$P = \frac{1}{\max(N_i, N_d)} \sum_{i=1}^{N_D} \frac{1}{1 + \alpha d_i^2}$$

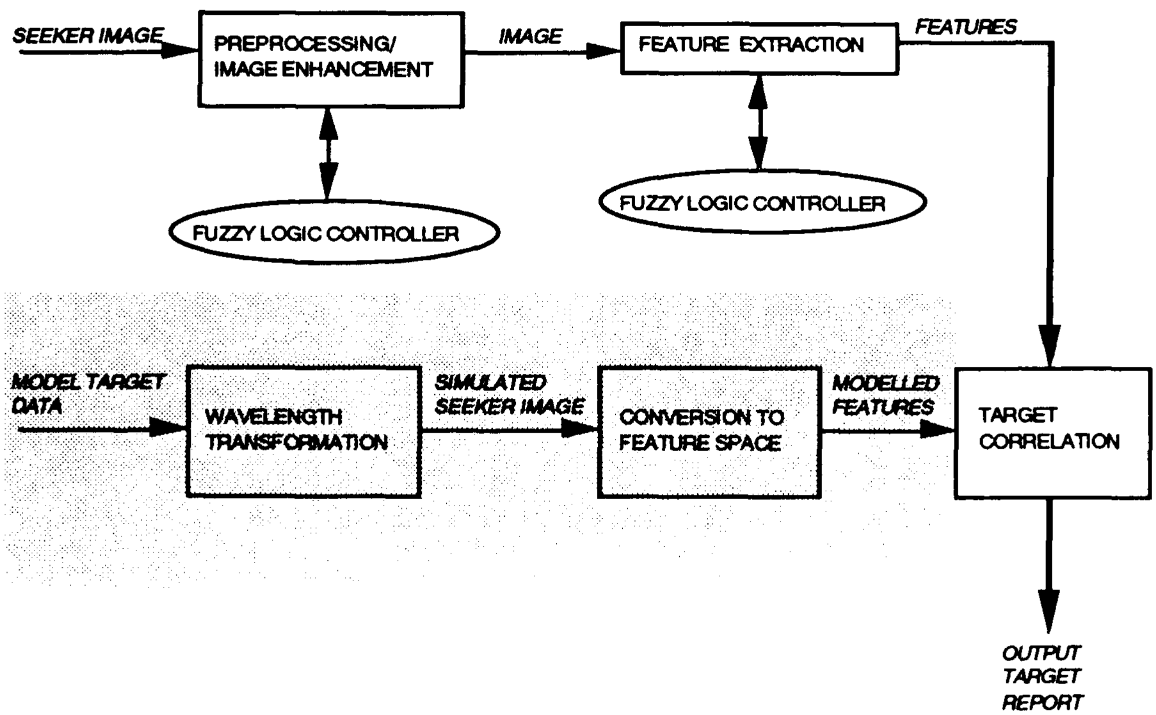

Fig 1. Structural Components of an Adaptive Autonomous Cuer.

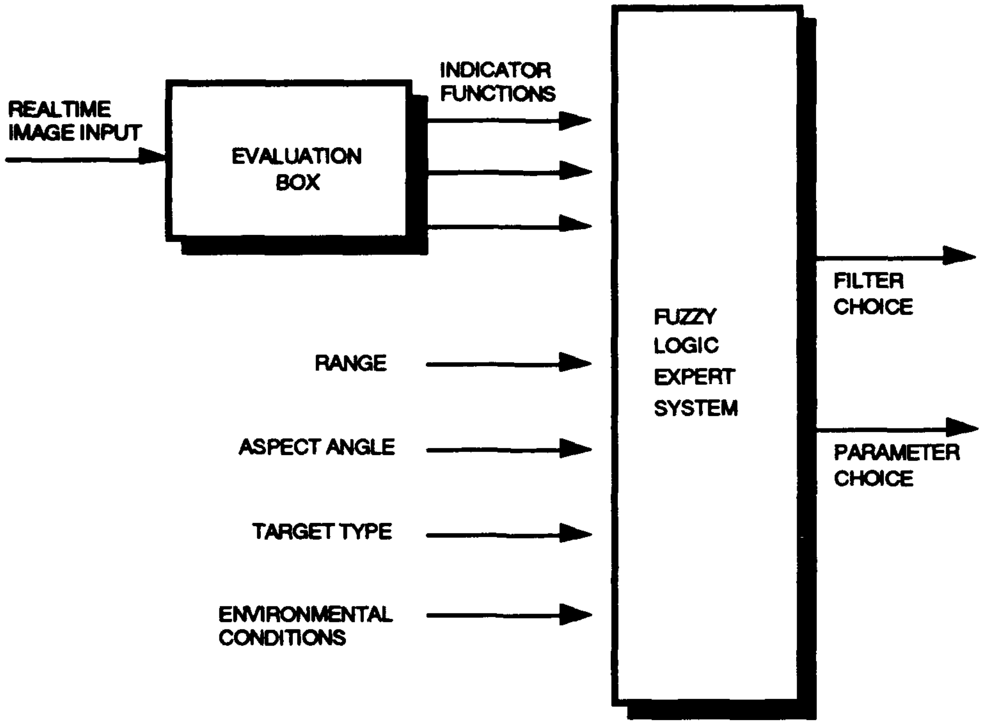

Fig 2a. Block Diagram of Fuzzy Logic Controller.

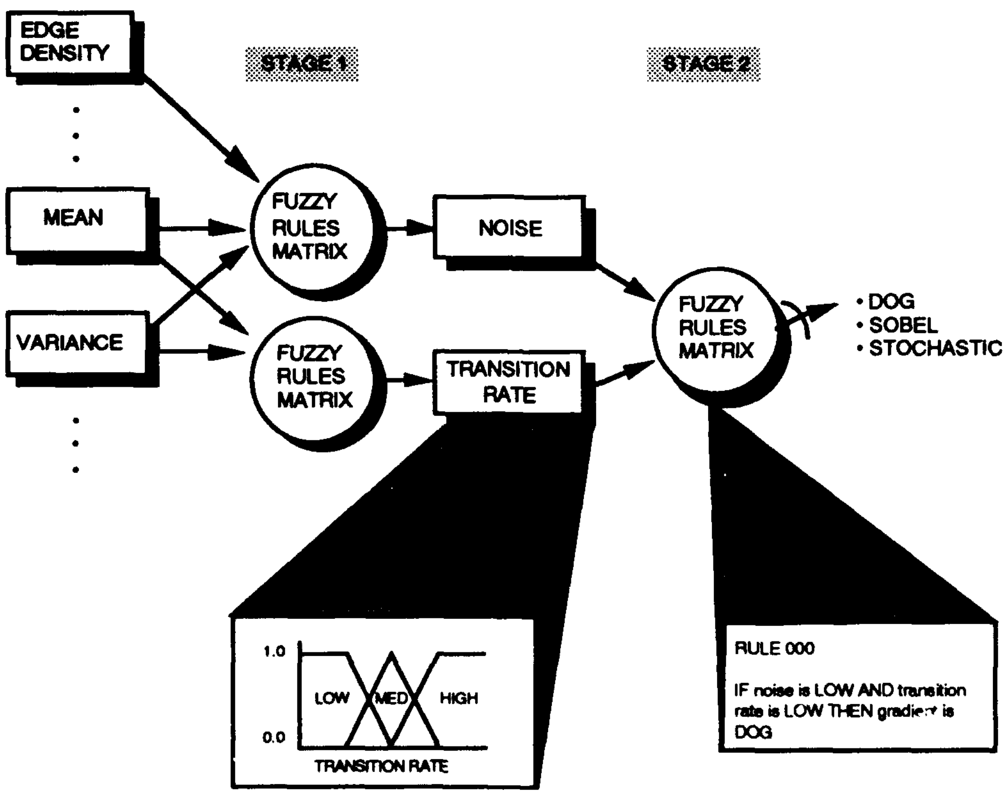

Fig 2b. Fuzzy Logic Expert System for Edge Extraction (DOG = Difference of Gaussian).

where d_i is the distance between a pixel detected as edge and the nearest predetermined ideal edge pixel; α is an adjustable constant; and N_i and N_d are the total number of expected edge pixels and detected pixels, respectively.

2. Perform a Taguchi experiment to determine under what conditions a particular filter will work best. For example, assign high, medium, and low values to the mean, variance, average gradient, range, visibility, and target size for the experiment. The outcome of the experiment will show which input parameters are important in determining which filter to use; and for the particular filter, conditions under which it will perform optimally. In other words, refine the fuzzy rules.

3. Repeat step 2 for each filter.

4. Remove those indicators or inputs that have the least effect on the performance of the system based on the results of the Taguchi experiments.

In the next section, we will show an example of the initial setup of a fuzzy logic controller to select an edge extraction filter.

EXAMPLE OF A FUZZY LOGIC CONTROLLER

For extracting edges from an intensity image, we know that a Sobel operator generally works quite well (Ref 6). However, a difference-of-Gaussian operator is better if the image feature contrast is flat or the contrast gradient transition is less abrupt, and a stochastic filter is preferred for very noisy image features. Based on this *a priori* information, a gradient selection membership function as shown in Fig 3 and a rules matrix for the controller as shown in Fig 4 can be set up.

A procedure was written to implement this fuzzy selection algorithm. The fuzzy control surface for the edge extraction filter is shown in Fig 5.

REMARKS AND CONCLUSIONS

An enabling factor for this system is the availability of faster and smaller computer hardware. Fig 6 illustrates the exponential increase in the processing power of large computer systems over the recent decades. This tremendous increase in processing power is achieved via faster clock speed, parallel processing on multiple CPUs, and smaller chip size. It is not unreasonable to assume that a teraflop computer that is small enough to be put on an aircraft could be available before the end of the century.

Another hardware solution is the use of special purpose chips. For example, the fuzzy logic controller can be mapped to special purpose existing fuzzy logic chip sets that can process 200,000 rules per second. Alternatively, the fuzzy rules can be mapped to analog artificial neural network hardware such as Intel's ETANN™ chip (Ref 7), which will only take 1 or 2 clock cycles to reach a result.

RESULTS

The proposed system is very flexible due to its interchangeable parts; and a new methodology, the Taguchi method, has been introduced to embed knowledge into an intelligent system. This system is a bold attempt to solve the nagging problem of system deterioration due to varying operational environments. If successful, this proposed system will perform equally well in the sands of Saudi Arabia or in the jungles of South America; in the middle of the day or in the dead of night; on a calm sunny day or in a driving rain storm. Such flexibility and robustness will go a long way in increasing acceptance of autonomous cueing systems.

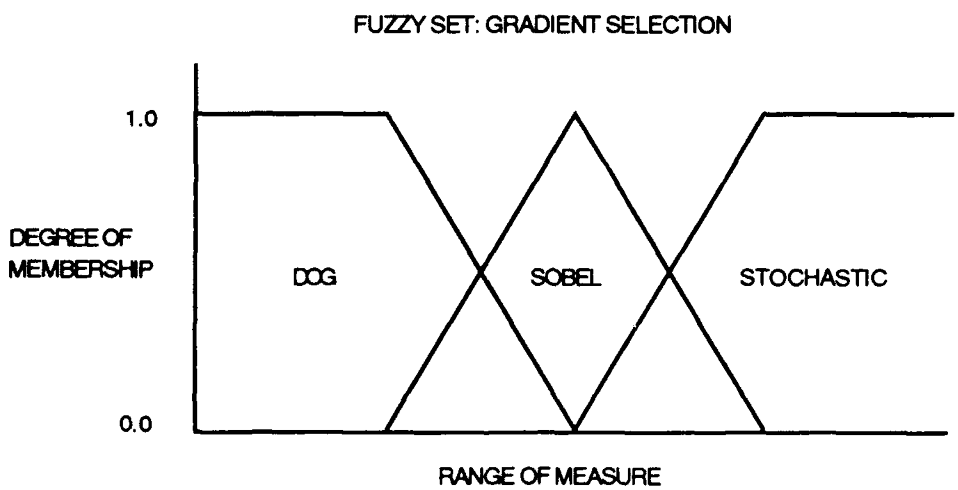

Fig 3. Stage 2 Gradient Selection Membership Function.

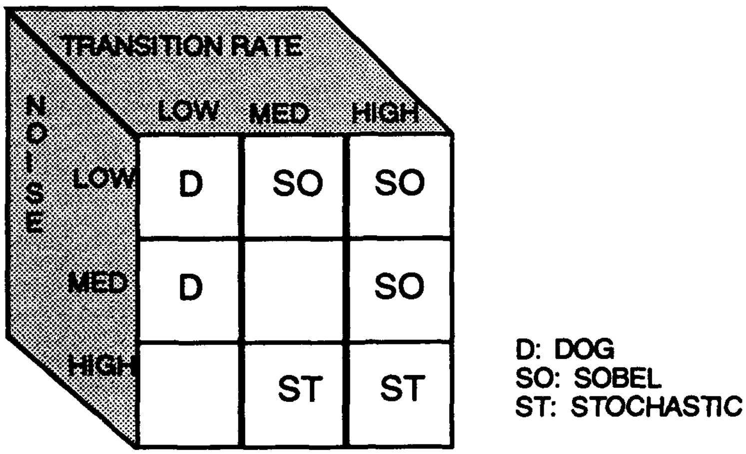

Fig 4. Stage 2 Gradient Selection Rules Matrix.

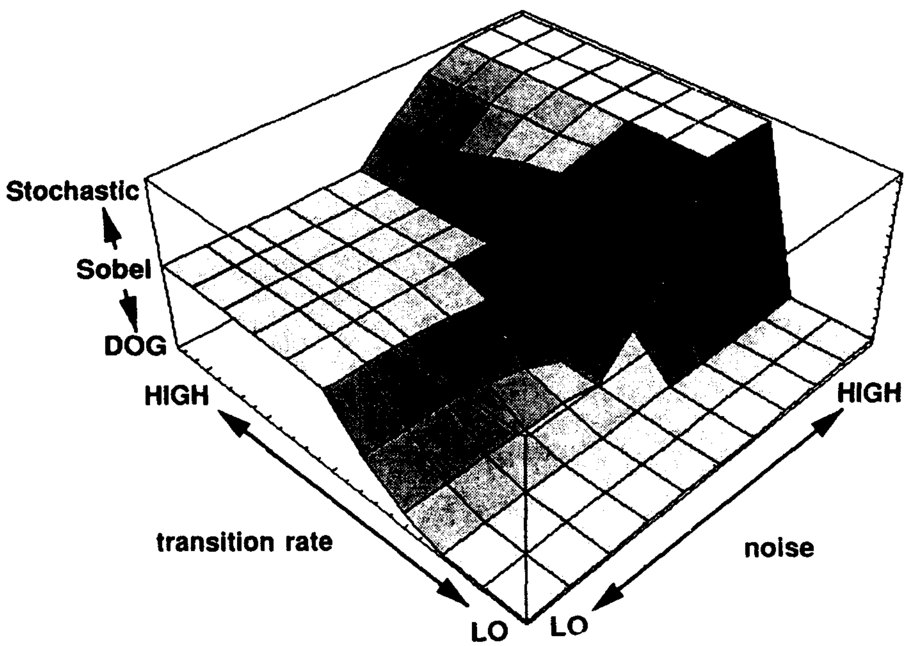

Fig 5. Fuzzy Control Surface for Gradient Selection.

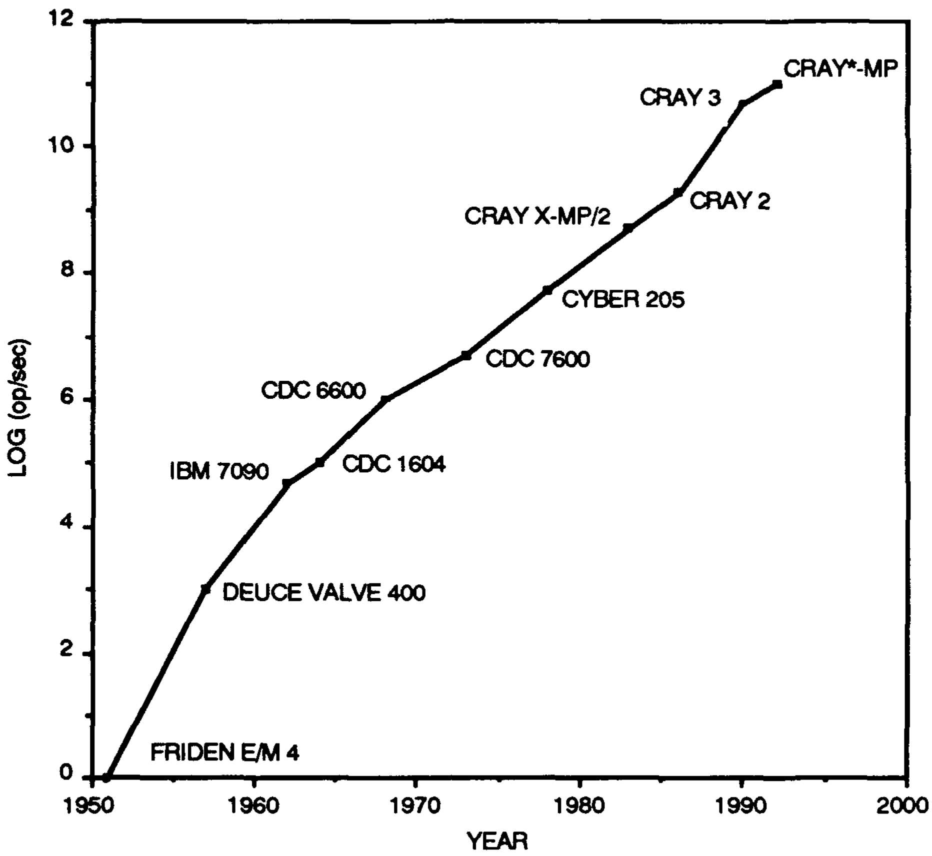

Fig 6. Processing Power of Computers (Computer Speed Versus Year).

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ANNEX A: A BRIEF INTRODUCTION TO FUZZY LOGIC

The objective of a fuzzy logic system is to use imprecise knowledge and rules in a particular situation to arrive at a particular conclusion or decision and to represent this in a modular structure. To accomplish this, however, it is necessary to address the issue of uncertainty. This issue is critical because much of the information in the knowledge base is imprecise or incomplete. Fuzzy logic is a formulation of logic that deals with such inherently fuzzy human concepts as

low, very, most, etc., in a rigorous mathematical framework.

In conventional set theory, a particular object is either a member of a given set or is not. In fuzzy subset theory, a particular object has a degree of membership in a given set that may be anywhere in the range 0 (not in the set) to 1 (completely in the set). While Boolean logic would require a statement to be true or false, fuzzy logic would assign a degree of membership to the set.

Fuzzy logic also defines operators on degree of membership values: AND, OR, and NOT.

Operator	Meaning
a AND b	the minimum of the degrees of membership for a and b
a OR b	the maximum of the degrees of membership for a and b
NOT a	one minus the degree of membership for a

Fuzzy subsets differ from conventional sets in that membership in a fuzzy subset does not have sharp boundaries. The mapping between the elements of the universe of discourse and their corresponding degree of membership in the fuzzy subset is referred to as the fuzzy subsets membership function. For example, we might define the fuzzy subset 'LOW noise' by Fig A.1.

Knowledge is specified to the expert system in the terms of production rules. For example:

RULE 000

IF noise is LOW AND transition rate is LOW THEN gradient is LOW

When the data value is fuzzy, the degree of membership is determined as the maximum degree of membership value for the intersection of the membership function for the fuzzy data value and the fuzzy set as shown in Fig A.2.

The process of applying the degree of membership computed for a production rule to the rule's conclusion to determine the action to be performed is called an inference. The concept is that the value to be assigned to the output is scaled or clipped to the degree of membership for the premise, and that all of the scaled or clipped sets for all of the rules that set this output are unioned together to form the final output membership function. The inference method results in fuzzy values. The centroid defuzzification method picks the output value corresponding to the centroid of the output membership function as the crisp and definitive value for the output.

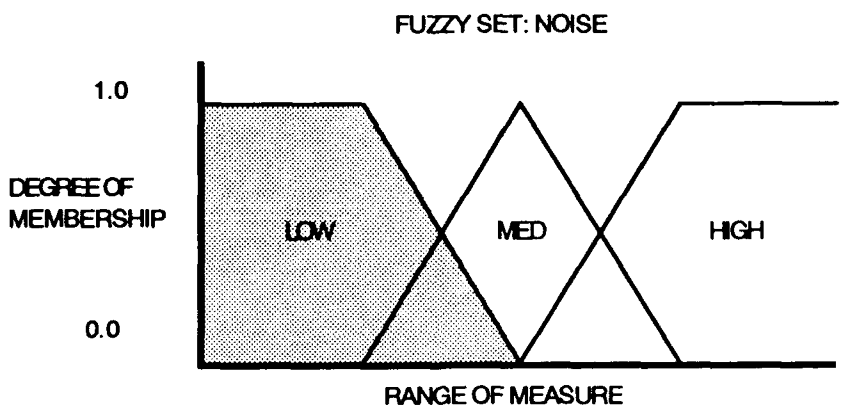

Fig A.1. Membership Function for Noise.

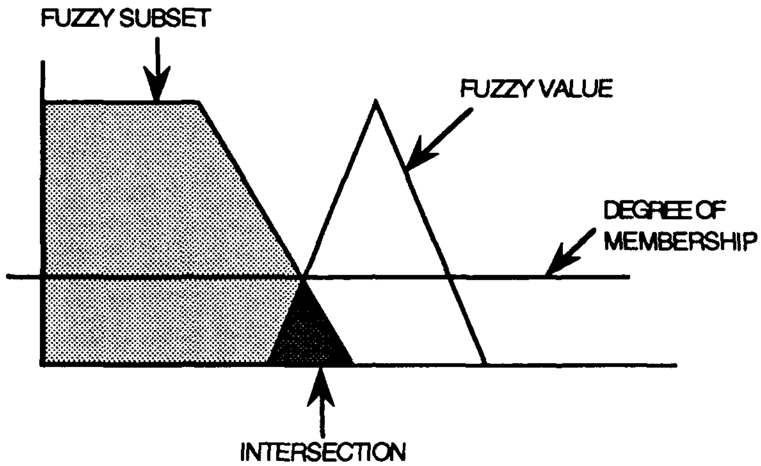

Fig A.2. Determination of Degree of Membership Value.

ANNEX B: A BRIEF INTRODUCTION TO THE TAGUCHI METHOD

The Taguchi method is a robust parameter optimization and quality control technique. The overall aim of all quality control activities is to produce a product that is robust with respect to all noise factors (uncontrollable factors such as temperature, humidity, individual operators, etc.). Robustness implies that the product's functional characteristic is least sensitive to variations that arise from the noise factors. Parameter design examines interactions between control factors and noise factors in order to achieve robustness. The Taguchi process is a search for parameter levels at which a characteristic is most stable. The technique of defining and investigating all possible conditions in an experiment involving multiple factors is known as the design of full factorial experiments. The Taguchi approach, using fractional factorial methods, investigates only a portion of all the combinations of production variable values and then estimates the specific combination of variable values that will optimize the desired results. The Taguchi method can save considerable time and money (as opposed to the full factorial method) in determining an optimum combination of variable values. However, the Taguchi method requires an investment in carefully planning the tests that are to be run and carefully adhering to the method during testing and analysis in order to optimize the success of its application. A special set of orthogonal arrays (OAs) is constructed to lay out the experiment. The OA facilitates the experiment design process. To design an experiment is to select the most suitable orthogonal array, assign the factors to the appropriate columns, and, finally, describe the combinations of the individual experiments (called the trial conditions).

The results of the experiments are analyzed to achieve the three objectives:

1. To establish the best or the optimum condition for the process.

2. To estimate the contribution of individual factors.

3. To estimate the response under the optimum conditions.

The technique is applied in four steps:

1. Brainstorm the quality characteristics and design parameters important to the process.

2. Design and conduct the experiments.

3. Analyze the results to determine the optimum conditions.

4. Run a confirmatory test using the optimum conditions.

Discussion

QUESTION J. DANSAC

Quand pensez vous que ces techniques seront adaptées dans des missiles?

REPLY

In about twelve years.

Equipment, more or less ready to be used in Helicopters

H.Hellmuth and Dr.H.-D.V.Böhm
Eurocopter Deutschland GmbH Germany
Avionics
Postfach 80 11 40
D-8000 München 80

SUMMARY

Today there is a long list of equipment proposed by the Equipment Industry ready to be used in a helicopter.
Once being in the situation to define system concepts for civil and military helicopters to fulfill a specific mission under several project boundary conditions, a closer look at these equipment will shorten the list dramatically.

Boundary conditions are for example :
- low price / low live cycle costs
- commercially available
- maintainability
- standard equipment
- short time availability
- ergonomic requirements
- flight safety
- mission effectiveness
- low crew workload
- vulnerability / redundancy
- integration constraints

There are technologies proposed on the market since several years which have not been used in series because of ineffectiveness or simply because of being not ready to be used.
For helicopters, there are specific requirements which limit the use of some equipment feasible for fixed wings.

This paper will show examples of equipment taken from project studies, and show the specific boundaries for helicopters. Avionic equipment, sensors as well as displays and controls will be covered. The paper will analyze equipment and technologies ready to be used today and in near future as well as equipment hardly usable. Equipment specific characteristics and helicopter/cockpit integration specifics will be covered.

1. INTRODUCTION

1.1 Helicopter Flight path

In contrast to the fixed wings, a helicopter flies lower. The so called Nap of the Earth (NOE) flying is performed in heights above ground between 3 and 50 feet (between 1 and 15 meters) at a speed of approx. 0 to 40 knots at night and 0 to 70 knots in daytime. This NOE flight is always performed by looking outside, heads up. Armed or "naked", the eyes must look out of the cockpit to guide the helicopter, to select the flight path. There is no time to look inside the cockpit. All additional information coming from sensors and systems must be presented head up.
This helicopter specific condition has to be kept in mind, while reading this paper!

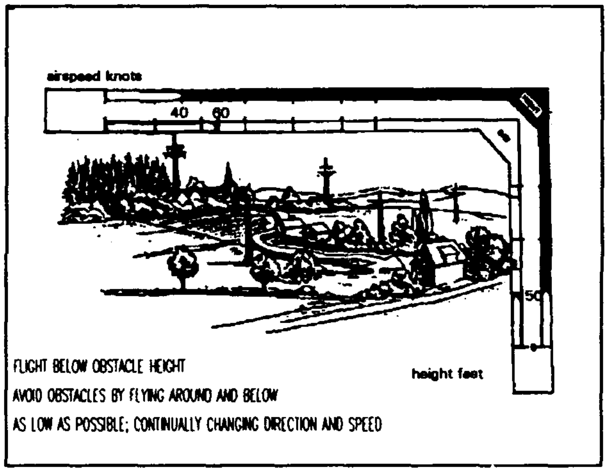

Fig.1 NOE Flight Path
(Source. ATV Bückeburg)

1.2 Bottleneck / Electro-magnetic Spectrum

At the beginning of aviation, the information was restricted mainly to that directly coming to the natural organs of sense like eye and sense of balance. More and more artificial sensors are being used, detecting signals of various wavelength which are translated into the area of natural perception.
These sensors are beginning with very simple ones like the magnetic compass or the barometric altimeter and nowadays ending with equipment like Infrared and Micro-Wave Radar Sensors.

The Electro-magnetic Radiation Spectrum:
Optical radiation is defined as electro-magnetic radiation in the range of wavelengths between 10nm and 1mm and can be subdivided into UV (Ultraviolet), visible radiation (light) and IR (infrared); compare Fig.3.
In order for a pilot to be able to see adequately at night or in bad weather, he must be provided with some artificial means of extending his optical range to

counteract the effects of poor light or atmospheric interference. Either, existing electro-magnetic energy levels need to be amplified electronically, or some method of observation must be used at wavelength which can effectively disregard atmospheric absorption owing to mist or fog particles. Fortunately, there are a number of narrow bands or "windows" in the visible and IR region of $0.3\mu m$ to $14\mu m$ for which atmospheric absorption is minimal, i.e. transmittance is maximal, compare fig.3.
The human eye responds only to optical radiation with wavelength in the visible region of the electro-magnetic radiation spectrum i.e. from $0.4\mu m$ to $0.7\mu m$. Two types of light-sensitive cells are present in the retina of the eye, the cones, used for colour vision in day-light, and the rods, not so highly selective in colour range, but most responsive to low-intensity sources i.e. at night.
Visual aids, in the form of multispecial electro-optic sensors, can be divided into 3 categories:
- Image Intensifiers (II)
- Thermal Images (TI)
- Image Micro-wave Radars (in near future)

Conspicuous is the fact, that almost all information provided by sensors and systems are transferred visually to the pilot.

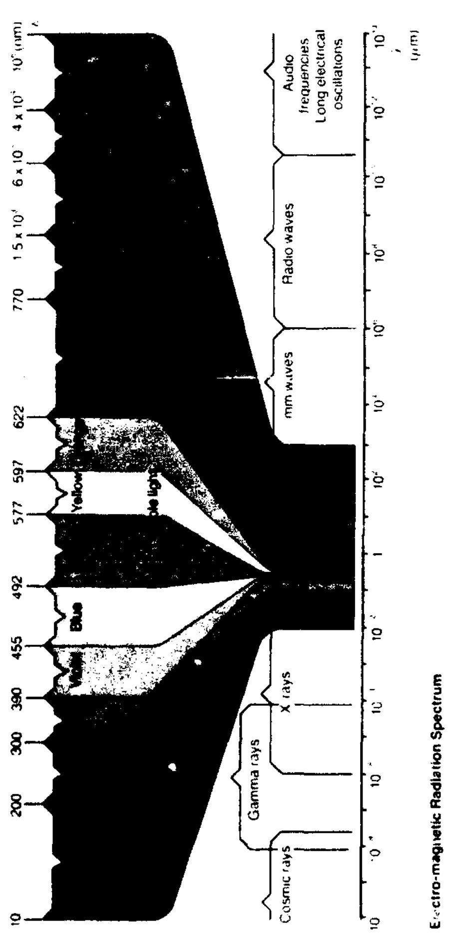

Fig. 2 Electromagnetic Spectrum

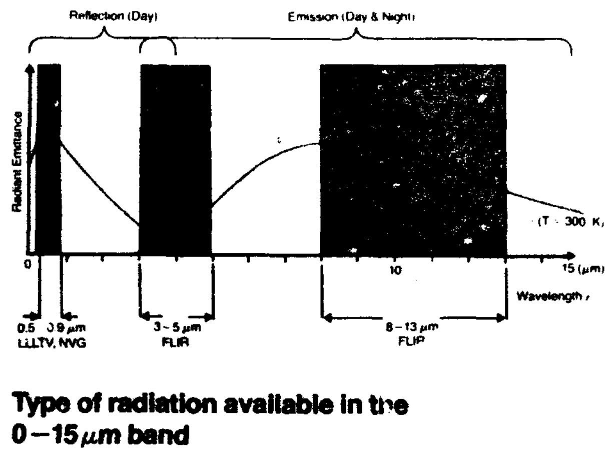

Fig. 3 Atmospheric Transmittance

The enormous increase of data due to the new sensors leads to a strong increase of pilots workload. The limit of faulty data processing by the pilot is reached. Careful selection of necessary data and its kind of presentation for specific mission situations is needed to avoid the overload of the crew.
Just as the cockpit provides information about systems and environment to the pilot, it receives orders/commands/controls from the pilot purely by manual action.
The one-sided use of human organs for information recording and command transfer is about to be broken. Attention ! Some techniques promise too much.

2. Visual Aids and Mulispectral Imaging Sensors

Image Intensifier (II) tubes as they are well known within Night Vision Goggles are integrated in the helmet together with micro-CRTs. This allows combination of II pictures and symbology and platform mounted sensors with symbology.
Thermal Images (TI) today have a good quality. They are used in the 3 to 5 and 8 to 12 μm spectral range for day and night application on a steerable platform in the helicopter. The steering arrays based on HgCdTe-detector materials with approx. 400 000 pixels per image (video standard) are not available today but the PSi-detector technology in the 3 to 5 μm band can be used without scanner. It is not necessary to cool down this detector up to liquid nitrogen temperature. A multi-stage Peltier cooling unit is sufficient.

Passive millimeter wave imaging radiometers are the future sensors to penetrate rain and fog better than TI. These sensors are used for signature research in satellites with remote sensing and on ground trails (ref.1 and 2) in the 35GHz, 94GHz and 140GHz range with GaAs technology. Active radar systems e.g. SAR (Synthetic Aperture Radar) or side and forward looking radar are good for battlefield surveillance.

Detection, recognition, identification and interpretation of multi-spectral visual aid information is the future technology called sensor or image fusion. The single components of such technologies are ready but the way to a lightweight and cost effective device will take some years. To this imaging sensors belong platform tracker, multi-target tracker and videomemory. A videomemory can store images of a landscape view for a short time. The pilot/copilot is than able to replay the scanned area behind safe obstacles.

3. Helmet Sensors and Displays

The requirements for a helicopter with night-flight capabilities have increased in the last years. The reasons are the experience with IIs and TIs in bad weather conditions in the European area. A pilot visionics system (PVS) consisting of a steerable platform with electro-optical sensors is controlled by a helmet-mounted sight (HMS), also called tracking system. The purpose of the HMS is to steer without an additional workload either a sensor-platform, a landing light platform or a weapon platform in accordance with the head motion of e.g. a H/C crew . The measured values of head motion angles must be of high accuracy and to be available with a minimum of time delay.

The helmet-mounted display (HMD) uses one or two mini cathode ray tubes (CRT) to provide a video image of the electro-optical sensor with superimposed symbology. With the help of a HMS-function the image can be roll-stabilized to keep the sensor image horizon aligned with the natural horizon when the pilot moves his head in roll.

Fig. 4 Integrated Helmet System (GEC)

Modern Integrated Helmet Systems (IHS) consist of CRTs for displaying binocular images of TV- or TI-cameras with superimposed flight symbology, see-through capability and integrated binocular Image Intensifier Tubes (IIT), compare ref. 3 and 4.

IIT with implemented CCD-Chip will be the future technology for the image fusion with TI and/or imaging MW-radar (active or passive) in an associated electronic box. The IHS represents the multispectral information on the binocular HMD for pilot aids.

4. Obstacle Warning Systems

Several manufacturers have completed basic development and first operational tests of Obstacle Warning Systems. Most of the systems are based on active millimeter radar sensors in the range between 35 GHz and 94 GHz but also on laser sensors in the 0.8 μm or 10 μm spectral range (refs.5 to 8). The systems in principle are functioning, including algorithms to identify the obstacles (in the most cases cables) out of a cluttered image.

Constraints:

- the sensor package, platform is very bulky and heavy
- integration of the sensor on a helicopter together with optical / thermal sensors for piloting aids and target acquisition and weapons firing is very difficult, because best places are taken by the other sensors already
- the equipment is very expensive, development costs will have to be paid by first serial integration.

In addition to all the above mentioned negative facts, there is still one big question to be answered;

"How do we transfer the information to the crew ?"

Three dimensional means of presentation for distance, azimuth, elevation/height and type of obstacle is needed. How do we avoid cluttering of display information? How can we display only that information which is not already presented to the crew by optical means like TI-pictures etc.?

We do not know the answer !

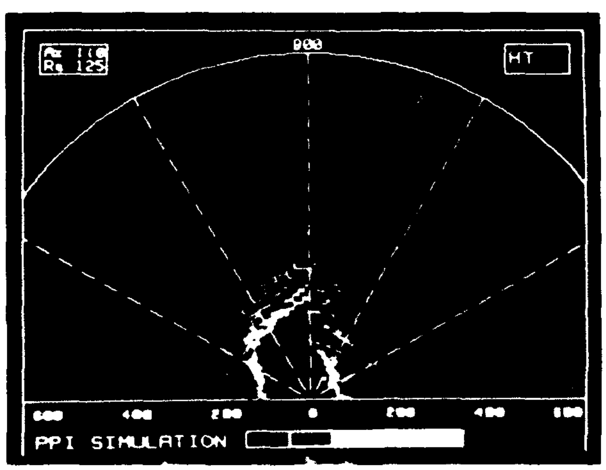

Fig.5 Obstacle/Radar Image of a Valley

Fig.6 Cockpit View of the Valley

Fig.7 3D-View DMA Data

It seems to us, that if the MMI problem can be solved (e.g. on an IHS with stereoscopic information presentation), the willingness to spend more money on the system final development (miniaturization, serialization) can be reached.
Obstacle Sensors are the only reliable means to avoid undesired contacts, no other sensor or equipment can replace it !

5. Electronic Maps

Electronic Maps are a perfect help to unload the crews knees. The word digital means, the map is stored as data and in most cases in a constant memory storage. Memory capacity and reading/processing time is no longer a limit. We see the digital map as a absolute must for today's and future military helicopter.
But there is a difference between on the market available digital maps, the data base.

- DMA-data or other three dimensional data is available to present a terrain model in 3D-view or 2D-view with height information to the crew. A more or less artificial image of the rough terrain is presented, just as if taken from a sensor.

Fig.8 2D-View DMA Data

- The other technique is to simply digitize paper-maps eventually in different layers (layers as they are needed to print in different colors by adding layer for layer: water, railroads, roads, buildings ......). These layers can be selected/combined individually to the desired combination needed to fly the mission.

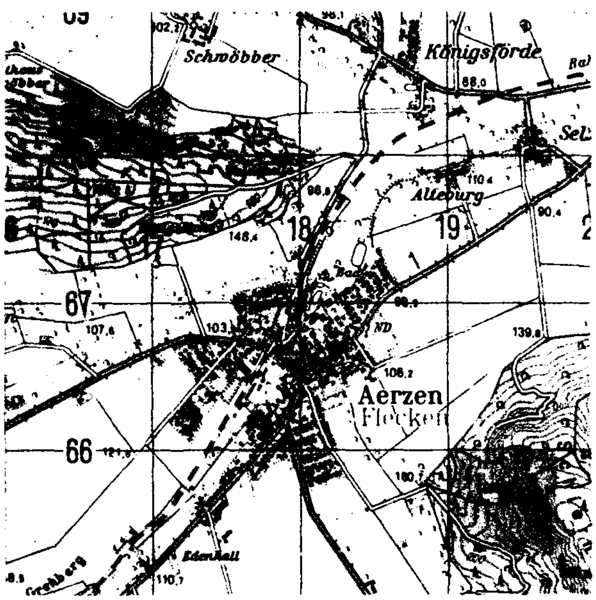

Fig.9 Scanned Paper Map

At a first look the 3D data and presentation appears to be the better one, but what does a low flying helicopter need?

The crew wants to know : "When I turn around that corner of the forest to my right, there is a house and a low electrical power line !".

This information today can not be given by a DMA data base but only by a digitized paper map.

Digitized pixel maps appear to us to be more realistic and effective during the mission because of its higher resolution. Obstacle warning and avoidance still can not be done with this equipment, but obstacle awareness is what can be attained. The combination of map and sensor at the moment promises to be the solution.

6. Voice Command

The reliability of voice recognition still is not sufficient to perform commands with any safety criticality. Mission safety relevant functions and by far flight safety relevant functions can not be transferred by this technique. What remains are relatively unimportant functions, not worth to spend money on.

7. Centralized Controls

Toady's military helicopters and those of tomorrow are carrying a vast number of equipment. All these equipment have to be controlled and monitored. Externally the cockpit must be kept as small as possible at least for better external vision. Because the space needed does not allow individual controls and displays - leading to a totally cluttered cockpit - centralization of controls and displays is necessary. Most of the actions in a cockpit are done to select what is to be monitored or controlled before actually doing it. There are techniques used to reduce these actions necessary before the initial task like automatic or coupled paging and moding, HOCAS (Hands on Collective and Stick) and some highly frequented specific controls and displays (e.g. RFI - Remote Frequency Indicators).

The paging tree of a typical Control and Display Unit is not trivial.

It is an absolutely necessary to have a clear basic dialogue throughout all pages and systems, even if not optimized for some of those. Paging, selection, scrolling, data input etc. must be performed in one way only.

8. Head In Display, Cockpit Integration

A totally different problem is the physical integration of HID type (Head In Display) of oculars into a cockpit. Originally these oculars where used to look through sight systems via direct view optics. Today the image in the ocular is seen on a high resolution, monochrome micro display. Up to now only these displays provide the resolution needed for target acquisition.

The head, covered by the helmet is trapped between headrest and ocular. When turning the head there is contact of the helmet and the ocular. Without partial movement of the ocular, work in the cockpit is more or less impossible.

Work is continuing to delete the ocular in the cockpit. Unfortunately the required high image resolution with equal vision angle is not provided by Head Down Displays (HDD) of normal size in the surface of the glare shield. Color displays suffer from principally lower image resolution over monochrome displays. Helmet displays with mini CRTs do not have the required resolution.

Fig. 10 Head In Display

9. Global Positioning System (GPS)

Obviously GPS is a low cost, easy to handle highly accurate navigation aid.

Nevertheless there are several constraints :

- Coverage; still there are holes when there are not enough satellites available!
- awareness of validity; still there is no quick (10 to 30 seconds) information about the status of the system provided, so you can not relay on the data, even if coverage is provided.
- only with additional installations (differential GPS) will accuracy be high enough for precise approaches and obstacle avoidance.
- There are no military and civil ATC procedures settled today to perform approaches or enroute navigation based on GPS alone.

Because of being very cheap, GPS is anyway used as a "nice to have" equipment, but never rely on it!

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Discussion

QUESTION: E.W. PIJPERS

In your paper you state that "electronic maps" would help unload the pilot's knee (folders). In my opinion electronic maps do not help as the pilot will still need a back-up or use the knee folder as a secondary source. Please comment.

REPLY

Back-up Paper Maps are still needed, but only in case of Electronic Map failure.

During normal mission there is no map in the cockpit needed (paper map), these maps can be stowed in relatively bad location

QUESTION: E.W. PIJPERS

In your paper you effectively exclude voice command technology for near term use in helicopters. I have to disagree to the inference made that there are no other functions being either safety critical or unimportant. Don't you foresee some essential functions which could be supported by voice command? Furthermore don't you feel that it is frequently the normal execution of non-essential tasks that interferes with the execution of essential and/or critical tasks?

Reliability is a different issue from the error occurring during operation.

On principle I have to agree to your statements. Nevertheless, using today's and tomorrow's voice command technologies, whatever function you would like to perform, the procedure (e.g. indicating that a voice command is coming, selection of the function, giving the command, getting feedback, confirming this...) will increase actions and workload.

In case a critical function must be performed, the pilot must concentrate on that, any other command, by voice or manually, will be postponed, until the critical functions/commands are completed.

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13. Keywords/Descriptors

Man-machine	Helmet mounted display
CRT	Advanced cockpit
Flight panel	Virtual display
HMD	Voice technology

14. Abstract

This Symposium explored the use of three of man's senses (sight, hearing, touch) to improve the man-machine interface in the cockpit. The seven sessions included Defined Concepts and Design Issues, Maintenance for Advanced Cockpit Systems, Panoramic and Virtual Cockpits, Helmet Mounted Displays, Voice Technology, System Concepts and Design Tools, and finally Device Technologies.

As the demands placed upon the aircrew by the modern battlefield continue to increase, this Symposium attempted to effectively blend the technologies available to decrease the workload.

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Advisory Group for Aerospace Research and Development, NATO
ADVANCED AIRCRAFT INTERFACES:
THE MACHINE SIDE OF THE MAN-MACHINE INTERFACE
Published October 1992
312 pages

This Symposium explored the use of three of man's senses (sight, hearing, touch) to improve the man-machine interface in the cockpit. The seven sessions included Defined Concepts and Design Issues, Maintenance for Advanced Cockpit Systems, Panoramic and Virtual Cockpits, Helmet Mounted Displays, Voice Technology, System Concepts and Design Tools, and finally Device Technologies.

P.T.O.

AGARD-CP-521

Man-machine
CRT
Flat panel
HMD
Helmet mounted display
Advanced cockpit
Virtual display
Voice technology

As the demands placed upon the aircrew by the modern battlefield continue to increase, this Symposium attempted to effectively blend the technologies available to decrease the workload.

Copies of Papers presented at the Avionics Panel Symposium held in Madrid, Spain, 18th—22nd May 1992.

ISBN 92-835-0689-8

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